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EVALUATION OF QUANTITATIVE ENVIRONMENTAL STRESS SCREENING (ESS) METHODS

Litton Systems Canada Limited

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The objective of this study was to evaluate Environmental Stress Screening (ESS) techniques contained in DOD-HDBK-344, by applying the methodology to several electronic products during actual factory production. Validation of the techniques, the development of improved, simplified, and automated procedures and subsequent revisions to the Handbook were the objectives of the evaluation. The Rome Laboratory has developed techniques which enable users to plan, monitor, and control ESS PROGRAMS. These techniques were previously documented in DOD-HDBK-344, "ESS of Electronic Hardware." The basic approach to the ESS process used in the Handbook focuses on the latent defect population of the hardware, and on developing a cost-effective, statistically controlled ESS process aimed at reducing the defect population so as to achieve quantitative field reliability requirements. As a result of the study: the effectiveness of the Handbook methodology and techniques was confirmed and validated; recommended changes, additions, and deletions were incorporated into a revision of the Handbook and software package was developed to facilitate application of the procedures. The study has also shown that the Handbook procedures provide a much needed linkage to TQM approaches, wherein customer reliability and cost requirements are translated into a suite of goals that can be measured and controlled in a factory manufacturing environment. The revised Handbook and application/evaluation results are (see reverse)

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contained in Volume I. The software and user manual are contained in Volume II.

FOREWORD

Before DOD HDBK 344, the usual practices for environmental stress screening (ESS) involved the application of fixed screening regimens, often defined by contract. The disadvantages with this approach to ESS were that i) it was not known whether the reliability requirements were being achieved and thus whether or not the ESS was inadequate (or conversely too excessive), ii) there was no provision for replacing screening with defect prevention and demonstrated process control, and iii) the ESS program was not necessarily optimized for cost.

With the introduction of DOD HDBK 344, the application of ESS was changed from the predefined approach to a quantitative approach that emphasized the use of ESS to identify and therefore eliminate the causes of field defects, and to design and dynamically modify an ESS program that optimized the combined user and producer's cost of achieving the desired field reliability. The implemented ESS program was monitored and controlled using statistical process control techniques. With the DOD HDBK 344 quantitative approach, the ESS was thus custom tailored to suit existing requirements, design, and factory capabilities. The approach assumed that the user conducted the necessary surveys and studies to determine the actual stress levels to which the equipment was subjected and provided the quantitative approach to determine the adequacy and efficacy of the ESS program.

In order to assure that the DOD HDBK 344 approach and methodologies were practical and could be be implemented in an actual factory environment, RADC commissioned this study contract to apply the methodology to three equipment types. With the changes recommended in this report and reflected in a revised HDBK, the study confirmed the methodologies of DOD HDBK 344 and also revealed that the approach provides an important and necessary technique for translating customer requirements for cost and reliability into a suite of goals and requirements that can be measured and controlled in the factory. In this way, the HDBK provides a vital link for an effective Total Quality Management (TQM) program.

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1. Introduction

1.1 Purpose and Objectives. The purpose of DOD-HDBK-344 (HDBK) is to describe the quantitative methodology for designing, implementing and monitoring a cost effective ESS program. The objectives of the study contract were to validate the concepts and procedures of the Handbook by applying them to the production of actual equipment in a real world factory environment, amend the Handbook as necessary, and develop PC spreadsheet software to facilitate and automate the procedures. The study program is illustrated in Figure 1.1. As explained in this report, several changes had to be made to the concept and procedures of the Handbook in order to make them practical and viable. To overcome potential accuracy problems, the procedures were designed to maximize the use of users' data collected and controlled in a Statistical Process Control (SPC) environment. With a general use of these procedures by the industry, many of the existing uncertainties in the modelling equations and parameters will be resolved and a more accurate data base created.

The result of the study contract is a handbook on ESS methodology that has been successfully applied in an actual factory environment. The procedures developed are thus not only believed to be practical but provide a necessary Total Quality Management (TQM) link for translating customers' requirements for cost and reliability into factory requirements that relate to all levels from design through parts and materials procurement, inspection, assembly and test.

1.2 Organization of the report. This report is organized in 4 parts. Part A describes ESS concepts and methodology, outlines the purpose and objectives of the study contract, and describes the type of products designed and manufactured at Litton Systems (Canada) Limited and in particular the equipment used for the study and Handbook validation. Part B describes the application of the HDBK methodology to 5 equipments in production at LSL and the analysis techniques used to compare observed and predicted results. Part C describes the problems encountered with the handbook and describes the recommended changes. Part D provides the recommended and revised version of DOD-HDBK-344. The philosophy and mathematical modelling for ESS are discussed in Appendix A. Appendix B contains a description of the software toolkit and discusses procedures for obtaining copies.

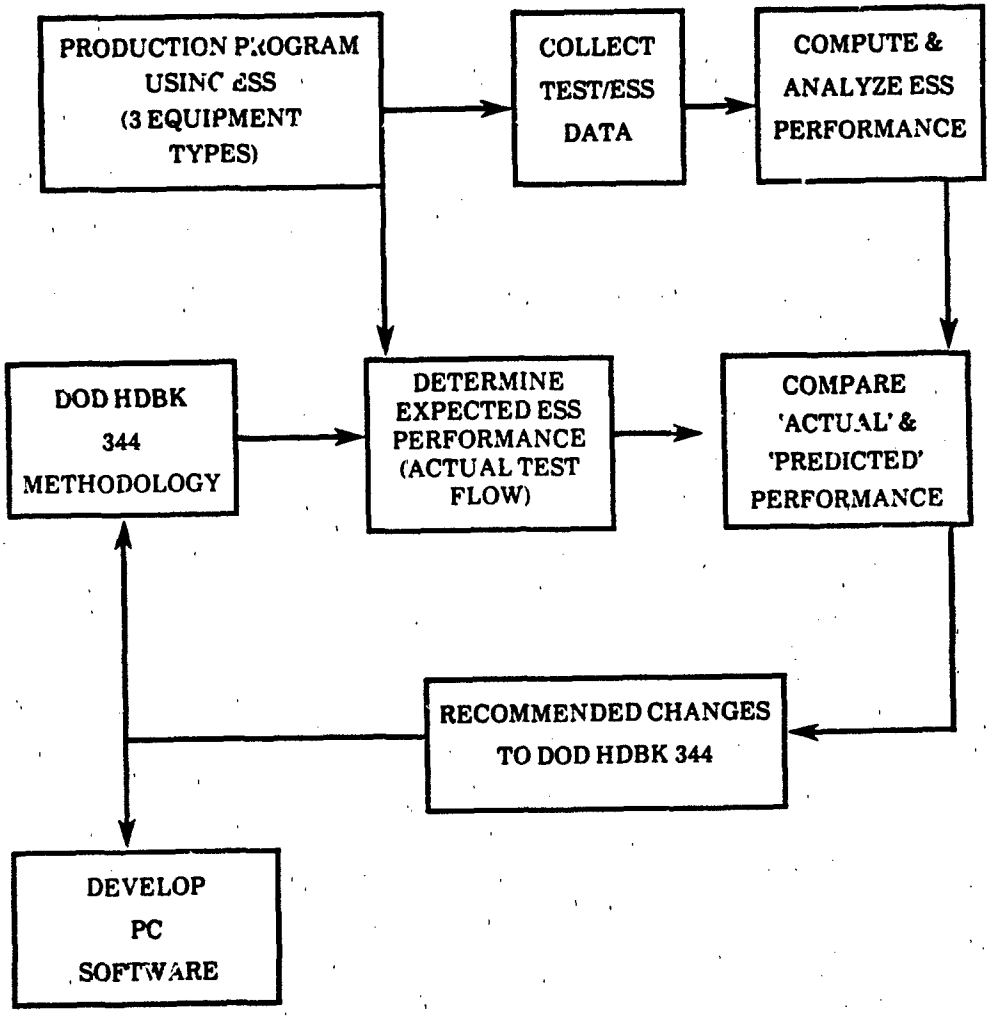


FIGURE 1.1 Study Program Outline.

PART A

I. INTRODUCTION

This part of the report provides an introduction to the ESS concepts used in DOD-HDBK-344, and describes the equipment selected for this study contract as well as an overview of the other products designed and manufactured at LSL.

2. ESS Modelling Principles and Concept. During the production of electronic equipment, defects are introduced through flaws in parts, materials, workmanship, and design etc. that affect the production yields and the reliability of the equipment. The reliability of a given design can be improved by:

i) reducing the number of defects introduced when the equipment is manufactured

or ii) removing the defects prior to shipment through test, inspection,and the use of ESS.

The former is the more desirable approach and will usually lead to both reduced production cost and improved field reliability. ESS is applicable to both approaches and has the principal purpose of exposing the existence and cause of defects in the equipment during development and production factory testing. Provided the defect causes can be eliminated, ESS serves as an in process monitoring tool. However, if the defect causes can not be prevented, then ESS serves the additional purpose of reducing the average number of defects per system to a level consistent with the reliability requirements.

In general, defects rates can be modeled as the result of either wear out mechanisms that affect the entire population, or flaws that affect only a portion of the population. Proper design practices, for example integrity analyses and concurrent engineering,should be used to prevent design errors and wear out mechanisms. The ESS methodology should be used to reduce the defects and failure mechanisms that affect only a portion of the population. In

practice, the majority of parts used in equipment are sufficiently free of defects so that, provided they are properly used, reliability is not impacted during the useful life of the equipment. There is however a small fraction of the parts that contain flaws that eventually cause equipment failure.These flaws or defects are the primary cause of equipment failure during the early life period. It is this small defect fraction, usually measured in defects per million (DPM) that is modeled and controlled by the ESS methodology. Because reliability concerns the fleet of equipment, the defects are usually measured as defects per unit. Throughout this report, the term defects thus refers to the average defects per system.

Conceptually, the application of stress causes weakness or flaws in a small fraction of parts in the equipment to grow until they cause equipment failure. The process of transforming a flaw with some residual strength; ie, a latent defect into a defect capable of causing equipment failure ie, a patent defect is called defect precipitation. The process of detecting a patent defect is called defect detection and requires the proper test to be performed. The stresses used in ESS to precipitate a defect are typically combinations of temperature, vibration, electrical, and occasionally humidity. These stresses are used because they accelerate defect precipitation so that the defect can be exposed and eliminated by factory ESS. Since the factory stresses are representative of field stresses, except at a higher and thus accelerating stress level, the defects removed through factory ESS are representative of the defects that would have otherwise occurred in the field. There is thus a direct relationship between the level of defects detected using factory ESS and field reliability. The HDBK ESS methodology thus addresses field reliability by quantitatively modelling and monitoring defect levels both in the factory and the field. Since the stresses used for ESS do not represent all of the field stresses and not all defect mechanisms can be sufficiently accelerated, a factory ESS program can not be expected to be completely effective and thus must be controlled using statistical monitoring techniques; eg, Statistical Process Control (SPC) supplemented with root cause physics of failure.

An Environmental Stress Screening ESS program, as defined in MIL-HDBK-344, (HDBK) provides quantitative techniques for i) assessing the initial number of defects, ie. defect density ii) designing an environmental stress

screening program to remove and thereby reduce the defects to an acceptable level, as determined by equipment reliability requirements, at an optimum production cost, iii) determining and eliminating the causes of failures through analysis and corrective action, and iv) applying statistical process control techniques to monitor and control the ESS program.

ESS modelling is based on the practical and mathematical premise that latent defects can not be completely eliminated and that achieving zero defects although an accepted ideological goal is unattainable in practice. Some level of failures or failure rate, although being undesirable, must be expected and thus be acceptable. The quantitative ESS methodology is concerned with determining and achieving the level of defects that can be tolerated.

In order to estimate the defects built into the equipment and removed by ESS, the methodology uses a combination of industry data for defect levels and screening strengths, and actual factory and field data obtained by the ESS user. The industry data contained in the HDBK is used for initial planning purposes until actual data is available, As actual data becomes available, the user analyses this data using the methods described in the handbook and updates the ESS plan so that it becomes an accurate representation of the actual conditions. In this manner, the accuracy of the HDBK methodology is not limited by the data contained in the HDBK that may be generic and not necessarily current.

For an effective ESS program, it is necessary to differentiate among the types of defects. Defects are caused by variability in parts and manufacturing processes and vary i) lot to lot, ii) with applied stress level and type, and iii) with time (life).

Defects can be characterized as latent or patent. A latent defect is an inherent weakness or flaw with some residual strength and will eventually cause equipment failure after exposure to s sufficiently high stress over some period of time. Latent defects do not cause a failure while in the latent stage and thus can not be detected until precipitated as a patent defect. A patent defect is a defect that has no residual strength and is capable of causing an immediate equipment failure given the proper circumstances. It can therefore be detected

in its present state provided the proper test is performed. Patent defects can be caused by a precipitated latent defect or manufacturing "error". The precipitation of latent defects into patent defects determines the equipment's reliability. Errors, such as test correlation, missing or incorrect parts etc are usually preventable or readily detectable and are typically removed from the hardware before shipment provided proper factory tests are performed. Although errors have the potential for impacting reliability, they can be eliminated without ESS and tend to impact production cost more than field reliability. The causes of errors are different than latent defects and thus should be addressed separately from latent defects for ESS planning and monitoring.

The ESS methodology fulfills a vital and necessary prerequisite for an effective Total Quality Management (TQM) program since it provides the technique for translating a customer's requirements for cost and reliability into a suite of design and factory requirements that are thus directly related to the customer's perception of satisfaction. The tools provide management with early visibility on the degree to which these goals are being achieved and an analysis capability to identify and resolve problems and to optimize the allocation of resources. The methodology thus ensures that the customer receives equipment that meets reliability requirements with an optimum screening cost.

3. Litton Systems Canada Limited. Litton Systems Canada Limited (LSL) is a major operating division of Litton Industries, and has been designing and manufacturing sophisticated electronics equipment for military and commercial use for over 25 years. Although initially involved in Inertial Navigation Systems (INS), LSL has expanded the manufacturing, design, and system engineering capabilities to a diversified capability and range of products.

3.1 Inertial Navigation Systems. Litton systems Canada Limited (LSL) was established in 1960 as an inertial navigation systems house. Having demonstrated the capability to manufacture INS, LSL has continued to expand and develop its INS-related capabilities to cover a range of both military and civil systems. This has resulted in a facility with total capability

in manufacturing, engineering and systems management. The production facility meets the critical standards of the military and civil aviation organizations.

To date, more than 12,000 inertial navigation systems have been produced at LSL, representing a significant portion of all commercial inertial navigation systems in use worldwide. Military systems manufactured by LSL are the LN-3-2A and 2B for the F-104, LN-12 for F-4, LN-14 for the F-111, LN-33L for CP-140, LW-33CF for the CF-104 retrofit, and Equipment A which is being produced by LSL for the U.S. Cruise Missile on a second source basis.

Production of Equipment A has led to the introduction of even higher standards of manufacturing facilities. Commercial inertial systems manufactured by LSL are the LTN-51, LTN-58, LTN-70 series and Equipment C series, used by airlines, in civil and military transport applications and in business aircraft. The LTN-76 is an INS used in special applications where extra precision is required.

LSL's inertial systems provide reliable, self-contained, all weather, worldwide navigation capability that is independent of external navigation aids. They are primarily designed for long-range aircraft, particularly on overseas routes, and they supply continuous, accurate position, navigation and guidance data. In addition, they are often used as the primary source of aircraft altitude and heading information.

3.2 Flight Inspection Systems. The Inertial Referenced Flight Inspection System (IRFIS) was developed by Litton Systems Canada Limited as a result of the desire of the Canadian Ministry of Transport to automate their Instrument Landing System (ILS) calibration facilities. Traditionally, Transport Canada, like many worldwide civil and military aviation agencies, calibrated ILS using manually operated theodolite techniques. Following an extensive series of studies and simulations performed by LSL, the Ministry awarded LSL a contract to design and build a more accurate, real-time calibration system, the IRFIS. The system underwent successful flight trials during the Spring of 1978 at the Canadian Air Force (CAF) photo-theodolite range at Cold Lake, Alberta, and has proven capability to calibrate Category I, II and II ILS as well

as en route navaids. The IRFIS represents the most sophisticated and advanced system of its type currently available.

3.3 Automatic Test Equipment Capability. LSL has been active in the design and development of general purpose Automated Test Equipment (ATE) for Military applications since the mid-1960s. ATE and LSL designed and developed Test Program Sets (TPSs) have been supplied to, and are in service with, military forces around the world. From the experience gained, a family of ATE has evolved which is capable of providing comprehensive, cost-effective support, at the Intermediate and Depot levels, for a wide range of electronic and hydraulic systems.

The basic member of this family is the Expanded Litton Automated Test Set (ELATS), which performs test and fault isolation on digital, analog and hybrid Weapons Replaceable Assemblies (WRAs) and Shop Replaceable Assemblies (SRAs). For testing WRAs and SRAs which operate in the radio frequency range, LSL has developed the RF/ELATS.

LSL has produced over four hundred TPS for a wide variety of electronic items. The electronic design, software and technical documentation associated with TPSs, can be produced either to best commercial standards or to full Military Specifications as demanded by such customers as the U.S. Air Force and the U.S. Navy. All Test Programs supplied for execution on the ELATS family are written in IEEE 716 ATLAS (Abbreviated Test Language for All Systems), which is an ARINC and U.S. DOD Standard.

3.4 Displays.

3.4.1 LED Display Systems. Since June 1975, LSL, initially under contract with the USAF and the Canadian Government and later under contract with the Canadian Government alone, has developed a solid-state, flat-panel display system using Light Emitting Diode (LED) technology for use in military environments. Throughout the program the Flight Dynamics Laboratory of the USAF at Wright -Patterson Air Force Base acted as the design authority.

LSL realized initial success with General Dynamics for Data Entry Display (DED) systems on the F-16C and F-16D Fighting Falcon aircraft. The full-scale development phase was completed and the first of over 2,000 production DEDs was delivered to General Dynamics in September, 1983. Strong growth in this contract and follow-on contracts continues today. Application of the base technology developed for LED display products lead to the design of programmable multifunction keypads. This product is used in strategic system control consoles in EC-135 aircraft.

3.4.2 Programmable Display Module. During the course of 1984, LSL adopted a vertically integrated approach to its display systems capability. While the company's major thrust remains directed at the large-scale complete systems opportunities, LSL nevertheless has expanded its efforts in the development of a modular or component capability.

The PDM has been designed specifically to meet the display requirements for a programmable switch or annunciator. Each of the PDMs 560 Light Emitting Diodes (LEDs), configured in a 16-inch by 35-inch array, can be individually addressed providing a complete alphanumeric and graphic capability.

Configured in an annunciator panel, the PDM effectively saves valuable cockpit or console space, reduces weight and provides a more cost-effective alternative to panels currently in use. Through combining several functions within a single PDM, the design engineer can create an annunciator panel which, in addition to the above advantages, is also beneficial from a human factors standpoint. Further, at point of retrofit, it does not become necessary to replace the panel, merely reprogram the PDMs.

3.4.3 Liquid Crystal Display. To supplement the flat panel display product line, LSL has designed and is expanding a manufacturing capability for Thin Film Transistor (TFT) active matrix liquid crystal displays. Colour displays up to 6 x 8 inch dimensions with 80 (colour) pixels/inch as well as monochrome displays have been produced.

3.4.4 Advanced Cockpit Display Systems. Starting in 1984 LSL initiated a major research and development program to establish display system

technologies appropriate to the cockpit display requirements of advanced military and commercial aircraft, scheduled for production in the mid-1990s. Evolving from this program are three distinct product types namely; colour active matrix liquid crystal displays, graphic processor modules and 3-D graphics software.

LSL's colour active matrix display technology offers a low-cost, lightweight reliable alternative to the multifunction shadow mask colour cathode ray tube display.

LSL's Graphic Processor Module (GPM) is being designed in cognizance of the United States Department of Defense Joint Integrated Avionics Plan for new aircraft. LSL's GPM will enable the display processing function to be implemented within an advanced avionic architecture based on the common module concept. The display processing function is to generate real-time complex 3-D imagery consistent with advanced display formats intended to increase pilot situational awareness and to decrease pilot workload.

LSL's 3-D graphic software, referred to as the Litton Graphics System (LGS), is a set of computer graphics interface commands, derived from the Programmer's Hierarchical Interface Graphic Standard (PHIGS) functionality for controlling the definition, display and modification of graphics data. LGS exists in an ADA language and is transportable from the application development workstation environment to the advanced avionic system environment.

3.5 Airborne Radar Systems. LSL entered the airborne search radar field in 1972 when the AN/APS-503 Airborne Radar System was designed and developed.

Subsequently, the APS-504 (V)2, a 100kW (peak) X-band airborne search radar system was designed for maritime search application, particularly against small targets in high sea-states. Functions include maritime surveillance, station keeping and mapping with a detection range extended out to 250 nautical miles. LSL (V)2 systems are now installed in seven types of aircraft, currently operational in seventeen countries around the world.

Continuing development of this family of radar produced the APS-504(V)5 [AN/APS-140(V)]. This latest generation radar provides a sophisticated Maritime Patrol and ASW capability. While retaining the field-proven scan converter and TV raster display of the (V)3, the (V)5 adds wideband frequency agility, 500:1 pulse compression using surface Acoustic Wave (SAW) technology, extensive sea clutter rejection circuitry and a Track-While-Scan (TWS) mode. Further development of the (V)5 to include Synthetic Aperture and Pulse Doppler techniques is currently being implemented.

3.5.1 Systems Engineering. Since 1966, when Litton Systems Canada Limited was placed under contract to provide the CCS-280 system for the Canadian navy's DDH-280 class destroyers, LSL has been the largest supplier in Canada of sophisticated Command, Control, Communications and Intelligence (C3I) information processing systems.

LSL has since expanded its scope to related roles, including Sustaining Engineering for the CP-140 Aurora Anti-Submarine Warfare (ASW)/Maritime Patrol Aircraft (MPA) Avionics/Electronics, Weapon System Integration, such as Command, Control and Communications Engineering for the Canadian Forces Low Level Air Defence System (LLADS) and also, Prime Contractor responsibility for the Tribal Class Update and Modernization Project (TRUMP).

3.6 Naval Systems Engineering.

3.6.1 Tribal Class Update and Modernization Project (TRUMP). Litton Systems Canada Limited was awarded the contract for the Tribal Class Update and Modernization Project (TRUMP) in 1986 to modernize and equip the ships with area air defence systems to meet the threat of the 1990s.

3.6.2 Automatic Data Link Information system. The Automatic Data Link Information Plotting System (ADLIPS) is a low-cost, shipborne, computer-assisted, real-time command, control and tactical data communications system which can be fully integrated with existing ship systems. The system collects and processes on-ship sensor data to generate a composite tactical picture to

facilitate operator action. It enables the ADLIPS fitted ships to communicate with each other, and with other ships and aircraft which already have data link capability, permitting the performance of coordinated tactical operations.

3.7 Airborne Systems Engineering.

3.7.1 CP-140 Sustaining Engineering. Involvement in the CP-140 program began in the mid-70s when LSL participated in the contract definition phase of the aircraft procurement program. Following contract award to Lockheed, LSL was selected as a subcontractor to Lockheed to develop and install the two DIACs, and to develop and produce the dual LN-33L Inertial Navigation System installed in each aircraft. The Litton Automated Test Set (LATS) was also provided for ground maintenance support of the LN-33L and other avionics systems.

In 1982, LSL was selected by the Canadian Defence Department to provide third-level maintenance for the CP-140 avionics systems.

3.7.2 Navigation/Tactical Computer and Display (NAV/TAC) System. The NAV/TAC is a low-cost, militarized, centrally controlled tactical information and display processing system. The system is based on the Motorola 68020 microprocessor and provides sensor control and mission control for an Anti-submarine Warfare (ASW) mission avionics suite. The system is designed for smaller fixed-wing or rotary-wing aircraft. The basic system is comprised of four major subsystems

a) A Tactical processor

b) An Input/Output processor

c) A Display processor

d) A Map processor.

Each subsystem includes an independent 32-bit microprocessor with local memory. In addition special processors are used for floating point calculations,

vector graphic generation, and map data expansion. The system architecture is based on the VME-bus for system interconnect, thus allowing a full 32-bit data path between subsystems. The display processor provides both vector and pattern graphics on a high-resolution bit-mapped RGB colour video display. Maps of 1, 024 nautical miles square can be generated, stored, and displayed with a resolution of 100 years with four planes of video bit map (1,280 by 1,024 by 4 bits).

3.7.3 Helicopter Integrated Processing and Display System (HINPADS). LSL is teamed with Computing Devices Company and Canadian Marconi Company to design and develop the Helicopter Integrated Processing and Display System (HINPADS) Advanced Development Module (ADM). HINPADS has been proposed as the core avionics suite for the New Shipborne Aircraft (NSA) program to satisfy the requirements for a Mission Systems Data Handling Subsystem (MSDHS), around which the NSA mission avionics can be integrated. The HINPADS ADM will provide the Canadian Department of National Defence (DND) with a validated, developmental model of a system which will provide integrated processing, control and display functions for a distributed, mission-oriented avionics suite.

3.8 Ground-Based Systems Engineering.

3.8.1 Data Interpretation and Analysis Centre (DIAC). In 1976, LSL was placed under contract by Lockheed California Company to provide a computerized, ground-based, data processing system to support the CP-140 Aurora ASW.MPA aircraft for the Canadian Forces. By 1981, LSL had delivered and installed two DIAC systems, at Greenwood, Nova Scotia and Conjox, British Columbia. These systems provide the Canadian Forces with aids for the briefing and debriefing of aircrews, mission planning, mission reconstruction and replay, the maintenance in dissemination of the tactical situation for ASW, SAR, fisheries protection and sovereignty patrol missions.

3.8.2 Canadian Forces Low-Level Air Defence System (CF LLADS). LSL is playing a major role in the CF LLAD program. In support of Oerlikon Aerospace (OA) of St. Jean, Quebec, LSL is providing essential production of major electronics subsystems as well as playing a leading role in systems

engineering by creating, developing, and supplying a sophisticated, high performance C^3 system.

There are two major electronic production projects for LSL, each of which has required a significant technology transfer and facility change. The production of Turret Electronics assemblies and electro-optical control consoles was preceded by extensive LSL participation in two separate subprojects. LSL undertook the maturation of the electronics design in order to facilitate production and to enhance reliability. Also, LSL hosted the OA and Martin Marietta-Oerlikon Aerospace (MMOA) teams for the Pathfinder program which integrated a complete weapons system using the production level electronics.

3.8.3 Security Systems. Litton Integrated Security Systems are turnkey installations which rely on LSL's extensive systems design capabilities. Typically, a group of subsystems providing functions such as perimeter and interior intrusion detection, entry control, CCTV surveillance, radio communications and automatic fault detection are coordinated and controlled by dual redundant computers.

Litton Systems Canada Limited has developed three integrated command and control systems for Correctional Services of Canada and has installed them in maximum security penal institutions at Saskatoon, Saskatchewan; Edmonton, Alberta and Agassiz, British Columbia. The systems use an acoustic fence sensor combined with a sterile zone monitored by microwave signals to detect attempted penetration of the perimeter fences.

LSL has supplied several perimeter and access monitoring Systems to Ontario Hydro for protection of nuclear power generating stations. The systems installed provide two separate and complementary methods of detecting intrusions into restricted areas so that a temporary single-point failure will not degrade the level of detection.

LSL's most recent success in security systems was realized when a competitive bid was won to install a major security system for the Royal Saudi Air Force (RSAF) base at Dhahran, Saudi Arabia.

3.9 Systems Engineering Support - Classified Modelling Facility. In support of its system engineering operations, and in support of the Canadian Government's Defence Research needs, LSL operates a Classified Modelling Facility. This facility is available to both industry (including LSL itself) and to government, on a contract basis. The facility is TEMPEST-secure, and is certified for operations to the SECRET level. Within the TEMPEST enclosure, LSL operates a Digital Equipment Corporation (DEC) VAX-11/750 computer and a DEC 2020 computer.

The configuration of these systems is compatible with the equivalent processors at the Defence Research Establishment, Ottawa, (DREO), and the Operational Research and Analysis Establishment (AE), to allow models to be transferred to the Government so that they may exercise without Contractor involvement. The CMF has available a number of defence scientists and software staff, capable of supporting applications in radar, electronic warfare (EW), communications, operations research and systems effectiveness analysis.

4. Description of the equipment used in the evaluation. As required in the RADC statement of work, LSL selected three different types of equipment for the study contract. In order to have an adequate data base for analysis purposes, equipment, with 2 or more years of production history were selected. Although LSL both designs and manufactures complex electronic equipment, LSL also manufactures equipment to other companies designs and drawing packages. The types of equipment selected for the study were "build to print" programs designed by three different companies. The selection of "build to print" over LSL designed equipment was made in the interest of greater objectivity in the data analysis, and also to provide a greater cross section of companies design approaches and part types. In this way the study was made more representative of the military electronics industry in general. The selection was also made to include a wider range of part reliability grades and packaging methods. Equipment A for example uses high reliability parts that are further upgraded through 100% parts rescreening at LSL. Equipment A uses both flat pack and through hole packaging and thus contains hand and wave soldered connections. Equipment B use high reliability grade parts with through hole packaging and thus predominantly wave soldered connections.

Equipment C uses high reliability grade parts but makes more extensive use of MIL-STD-883 level as opposed to full MIL-M-38510 level devices and is assembled using through hole and wave soldered connections.

The reliability and ESS programs applicable to the selected equipment are provided in the following. Details on the equipment complexity can be found in Part B.

4.1 ESS Programs used on the selected equipment

4.1.1 Equipment A, Military Inertial Navigation System. This equipment provides the inertial reference measuring unit and computer for a missile guidance set. The equipment consists of 23 complex electronic and/or electromechanical assemblies and contains approximately 3000 electronic parts. ESS is presently used at all levels as follows:

i) 100% parts screening and testing at vendor

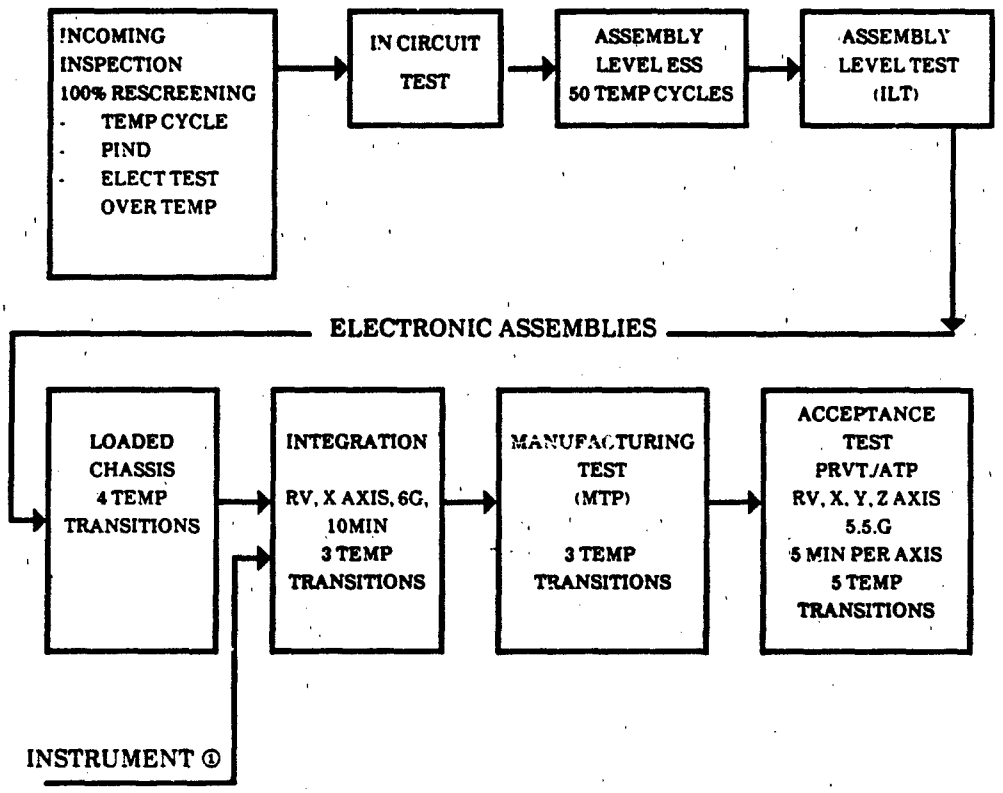
ii) 100% parts testing and rescreening at LSL Receiving Inspection

iii) Assembly (card) level ESS and testing using automatic test equipment (ATE) (e.g. in circuit testers) and/or performance and functional testing

iv) system level ESS and testing using ATE

v) system level failure free testing and reliability verification testing (PRVT)

The ESS flow is shown in Figure 4.1.



① NOT INCLUDED IN THIS STUDY

FIGURE 4.1 EQUIPMENT A ESS Flow.

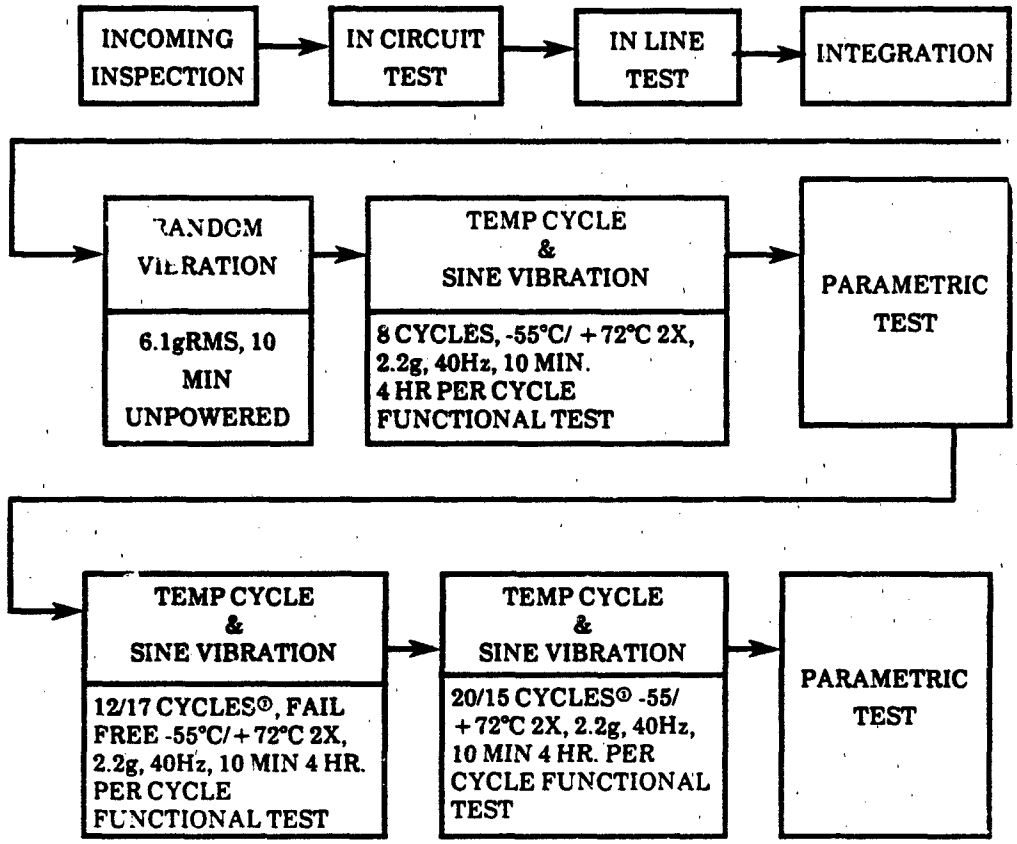
4.1.2 Equipment B, Display System For Fighter Aircraft. This equipment provides the displays for a fighter aircraft and consists of Heads Up Display (HUD), Multipurpose Display Indicator (MDI), and Multipurpose Display Indicator Repeater (MDRI). Each HUD consists of 18 complex electronic assemblies, each MDI consists of 22 complex electronic assemblies and each MDRI consists of 8 complex electronic assemblies.

The ESS program consists of part screening and testing at receiving inspection, assembly (card) level testing, and system level ESS. The outline of the ESS flow is shown in Figure 4.2.

4.1.3 Equipment C, Inertial Navigation System For Commercial Aircraft. Equipment C provides inertial navigation and reference systems for commercial and/or military transport aircraft. These are advanced systems using ring laser gyroscopes and, because of the application have quality and reliability programs and requirements similar to military equipment. For example, parts used are Quality Grade 3 as defined in MIL-HDBK-344. The factory testing and ESS program includes part testing and rescreening at receiving inspection on a sample and/or 100% basis, assembly level ESS and testing, and system level ESS and testing. The ESS test flow is provided in Figure 4.3.

4.2 Reliability Program Requirements for the selected equipment. The three equipment types selected for the ESS study have quality programs conducted in accordance with MIL-Q-9858. Equipment A & B have customer specified reliability programs that adhere to the tasks as specified in MIL-STD-785. The program for Equipment C has requirements which are similar or equivalent in purpose as noted in Table 4.1 through 4.3.

Tables 4.1 and 4.2 list the MIL-STD-785 tasks that are required by specification and/or imposed by LSL procedures and manuals, and list the tasks supported by the program plan. Table 4.3 lists the ESS related specifications that are imposed by the customers.



① MDRI and HUD/MDI respectively. All systems receive 40 Temp Cycles in total.

FIGURE 4.3 Equipment B ESS Flow.

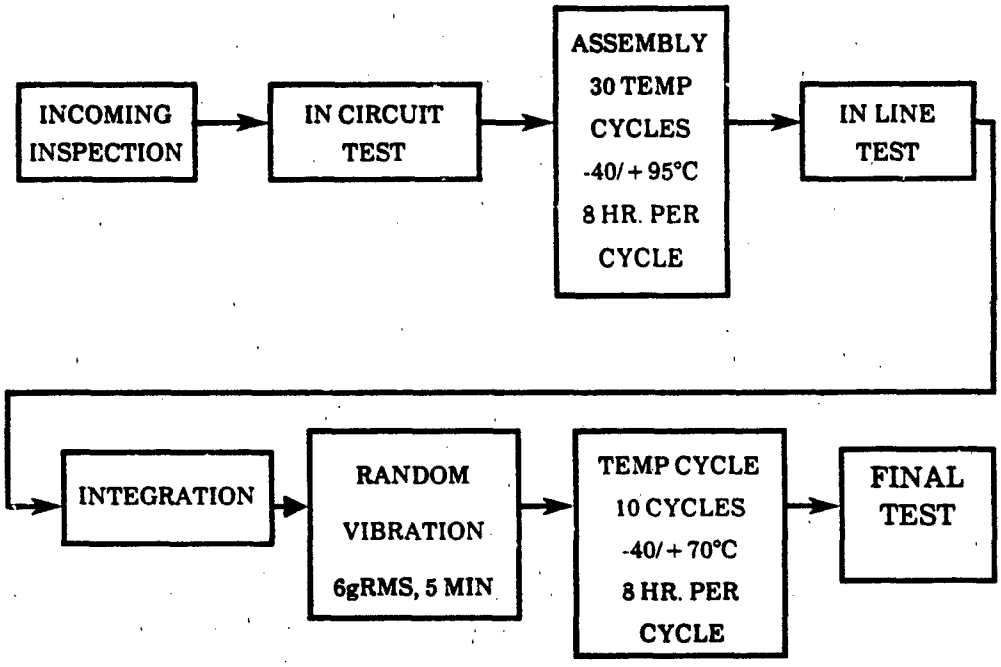


FIGURE 4.3 Equipment C ESS Flow.

TABLE 4.1 Equipment Program Surveillance and Control Tasks.

TASK #	MIL-STD-785 TASK	Equip-ment A	Equip-ment B	Equip-ment C
101	Reliability Program Plan	(1)	(2)	
102	Monitor/Control Subcontractors	X	X	
103	Program Reviews	X	X	
104	Failure Reporting, Analysis and Corrective Action	X	X	(3)
105	Failure Review Board	X	X	(3)

NOTES:

1. Program to MIL-STD-785 Rev. B.
2. Program to MIL-STD-785 Rev. A.
3. Commercial equivalent, integrated with LSL's FRACAS system which uses the same failure reporting, analysis and corrective action action elements that are shared with the military programs

TABLE 4.2 Equipment Design and Evaluation Tasks.

TASK #	MIL-STD-785B TASK	Equip-ment A	Equip-ment B	Equip-ment C
201	Reliability Model	X	X	(1)
202	Reliability Allocations	X	X	
203	Reliability Predictions	X	X	(1)
204	FMECA	X	X	(1)
205	Sneak Circuit Analysis		(2)	
207	Parts Program	X	X	(1)
209	Effects of Testing Storage and Transportation	X	(3)	
301	Environmental Screening [ESS]	X	X	X
302	Rel Dev. Growth Test [RDGT]	(4)	X	(5)
303	Rel Qualification Test [RQT]	(4)	X	
304	Production Rel Acceptance Test [PRAT]	X	X	(6)

NOTES:

1. Completed to commercial equivalent to military requirements. The main difference is no formal data item description [DID].
2. Informal (no DID) sneak circuit analysis required. Results available upon request by customer.
3. Only description of packaging methods and materials required.
4. Verification by analysis, supplemented by field data.
5. Completed to commercial equivalent of the military requirements. No formal data items descriptions. Reports tailored to company standards.
6. Commercial equivalent, integrated with LSL's FRACAS system which shares the same failure reporting, analysis and corrective action elements with the other in-house military programs.

TABLE 4.3 Miscellaneous 'ESS Related Specifications' for the Equipments.

SPECIFICATION	ITEM DESCRIPTION	Equip-ment A	Equip-ment B	Equip-ment C
MIL-STD-965	Parts Control Program	X	X	(1)
MIL-STD-1520	Corrective Action System	X	X	X
NAV MAT P9492	Navy Manufacturing Screening Program	X	(1)	(2)
MIL-STD-781	Reliability Tests, Production	X	X	
MIL-STD-1631A	Procedure for Selection of Electronic Parts		X	
MIL-STD-1535	Supplier Quality Assurance Program Requirements	X		
MIL-STD-1695	Mil Standards for Working Environment	X		
NAVMAT INST 4855.10	Contractual Manufacturing Requirements		X	
MIL-Q-9858	Quality Program Requirements	X	X	X

NOTES:

1. Customer specified equivalent.
2. Litton specified equivalent.

PART B

1. Introduction. The procedures of DOD-HDBK-344 were applied to the equipment described in Part A in order to assess the methodology and handbook accuracy under factory conditions. This part of the report describes the application of the handbook's procedures, the methods used to collect and analyze factory data, and conclusions and recommendations from the analyses.

2. Application of DOD-HDBK-344

2.1 ESS Application Constraints. The ESS procedures for designing and monitoring an ESS program are described in Section 5 of the handbook. Because the equipment selected by LSL was currently in production, it was necessary to apply the HDBK procedures in retrospect. Further, the ESS performed on the equipment was defined contractually and thus could not be altered to suit the study contract. The study program approach was thus to use the HDBK to model the actual ESS being conducted on the three equipment types and then to compare the observed factory results to the HDBK's predictions. The viability of the methodology and procedures and the HDBK accuracy could thus be assessed. The analysis techniques used and the results are discussed in this section.

2.2 DOD-HDBK-344 Methodology Overview.

2.2.1 Methodology Overview. The ESS concept and methodology described in the HDBK is a quantitative approach that establishes a relationship between field reliability and the defects remaining in equipment at the time of shipment. The field reliability requirement can be defined in terms of an average MTBF or failure free percentage measured over a specified time interval and conditions. The ESS methodology directly relates these requirements to a maximum level of defects per system that can exist when the equipment completes factory testing. The methodology also estimates the level of defects that exist when the equipment is manufactured. The ratio of the maximum allowable defects per system at time of shipment to the number of defects per system introduced during manufacturing determines what fraction of defects must be removed through inspection,testing, and ESS. The

effectiveness of removing these defects is quantitatively measured by the screening strength of ESS. Screening strength is governed by the ability to precipitate a latent defect to a state where it can be detected, ie precipitation efficiency, and the the ability of a test to detect and isolate the precipitated defect ie detection efficiency. The stresses used to precipitated and detect defects are representative of the stresses that the equipment will see in operation, storage, transportation, and maintenance etc but at higher and thus accelerating levels. The defects removed through factory ESS are thus similar to the defects that would have occurred in the field if ESS had not been performed and thus, there is relationship between factory fallout and field reliability for both causative effects and levels.

To apply the ESS methodology, the user of the HDBK must determine the following key parameters:

i) Incoming defect levels. Although the majority of parts and workmanship operations are defect free, some small fraction will contain flaws or defects that can be measured as a defect density in defects per million. The sum of the defects from parts and workmanship operations determines the total defects per system. It is the average defects per part, workmanship operation, and thus system that must be determined to apply the ESS methodology.

ii) Screening Strength. The probability of a screen being able to precipitate, detect, and remove a defect is measured by its screening strength. Screening strength is the product of precipitation efficiency, determined from the type, level and duration of the stress, and detection efficiency, determined from the probability that a test will detect, and isolate a particular fault.

These parameters and other HDBK requirements are discussed in the sections that follow.

2.2.2 Estimating Incoming Defects. The ESS methodology as described in the HDBK procedures estimates the incoming defects based upon the equipment complexity and the reliability level of the various parts and processes. This is

accomplished by describing the equipment in terms of the quantity of items within various part-process categories and multiplying these by an expected fraction defective for each of the part-reliability grades and process types. The fraction defectives are determined using lookup tables found in the HDBK and have different values depending upon the end application operating environment. The term fraction defective is used in the handbook to describe the number of defective electronic parts per million used. For consistency ,it is recommended that the term Defect Density be used to denote the normalized defects per unit of any item, whether it is a part, assembly, or equipment. The units of defect density are defects per million (DPM) or defects per unit (DPU) as appropriate. The term defect density shall be used throughout this report (and the recommended revised version of the handbook) in favour of the HDBK term fraction defective. The procedure for estimating the incoming defects is Procedure A.

Because HDBK defect density data is generic and may not be sufficiently current for certain programs, the recommended HDBK changes contains a methodology for determining defect densities from observed factory and field data. These data would be used in preference to the HDBK tables provided sufficient data has been collected and validated.

2.2.3 Estimating Screening Strength. The next step is to estimate what fraction of the latent defects is removed by ESS and to optimize the screen type,selection, and placement. The method for doing this is described in procedure B of the HDBK.The terminology used in the current HDBK denotes the strength of a screen as Test Strength,and the effectiveness in precipitating a defect as screening strength. These terms can possibly lead to confusion and inadvertent misapplication; thus, this report and the recommended changes to the handbook redefine these terms. With the revised terminology, a screen is used to remove defects by precipitation and detection. The effectiveness of a screen is thus measured by its screening strength and is determined from the product of a precipitation and a detection efficiency term.To apply the procedure, the HDBK user determines the precipitation efficiency for a given stress type,level, and duration using lookup tables or solving equations that are provided in the handbook. The test detection efficiency is determined based on the type of testing performed and whether testing is performed during

exposure to stress. The screening strength is then determined from the product of these factors. To improve the accuracy of this estimate of screening strength, the revised HDBK contains a methodology for determining screening strength from actual factory and field data. The value obtained from the observed data would be used in preference to the HDBK tables provided sufficient data has been collected and validated.

2.2.4 Failure Free Acceptance Test. A failure free acceptance test (FFAT) is designed using Procedure C and has the purpose of demonstrating that the remaining defect density is adequate for the desired reliability. The FFAT in itself uses ESS to precipitate a fraction of the remaining defects. The number of defects precipitated and removed is related to the defects remaining and thus is an indicator of residual defects and thus reliability. The HDBK procedure was found to be deficient and had to be modified to be implemented for the study. The reasons for the changes and other concerns with the procedure are discussed in 2.9.

2.2.5 Cost Effectiveness Analysis. The cost effectiveness analysis used as part of procedure B to optimize the ESS program is described in Procedure D. In principle the user determines the total cost of the factory ESS program and compares the cost per defect removed to a representative cost of a field defect ie $1000 that is called the threshold cost. The intent is to optimize the ESS program based on the combined cost to the producer and customer. The implication is that if ESS costs the producer more than $1000 per defect then perhaps a portion of the ESS (hence cost) is unwarranted and its necessity should be determined by the procuring activity.

2.2.6 Monitoring, Evaluation and Control. Monitoring, evaluation, and control of the ESS program are accomplished using quality control charts and are described in Procedure E. The ESS parameters of interest are initial defect density (Din) and TS (now called SS) with potential problems being identified by these parameters being either higher or lower than expected. An inherent difficulty however, is that neither of these parameters are directly observable by the user;hence, methods of estimating them from factory fallout are also provided.

2.3 Application of DOD-HDBK-344 procedures. This section describes the application for the handbook procedures to the three equipments selected for the study contract.

2.3.1 Designing ESS Program in Retrospect. In order to apply the HDBK methodology, it was necessary to design the ESS program in retrospect. This was accomplished by applying the HDBK methodology to

i) estimate screening strength
ii) determine initial defects per system prior to ESS
iii) determine defects removed and remaining throughout ESS

2.3.1.1 Step 1, Determine Screening Strength.. The screening strengths were computed using the equations that were used to create DOD-HDBK-344 tables 5.14 - 5.18 (courtesy of Al Saari, Hughes Aircraft Company of Fullerton, California). The use of equations rather than look-up tables provides greater flexibility and accuracy since the tables do not include all of the appropriate conditions or parameters. For example, Equipment A assembly level ESS uses 50 temperature cycles whereas Table 5.15 only goes as high as 12 cycles.

The screening programs for the equipment (Part A Figure 4.1, 4.2, and 4.3) were thus modeled and the results summarized in Figures 2.1, 2.2, and 2.3 for Equipment A, B, and C respectively.

2.3.1.2 Step 2, Define the Complexity. The initial defects per system were calculated by multiplying the number of parts in various part types and reliability grades by the appropriate defect densities found in the HDBK Tables 5.2 to 5.13.

The complexity of equipment A, B, and C are provided in Figures 2.4 through 2.8. The complexity of equipment B has been described for each of the major systems, i.e., MDI, MDRI, and HUD.

Test Level	Environment	Precipitation Efficiency	Stress Parameters
Card-Module	Temp Cycle	.99	50cycles,15C/min, 130 C range
Module	Rand Vib	.96	12 gRMS, 10 min
System			
Pre integration	Temp Cycle	.65	4 cycles, 5 C/min, 125 C range
Integration	Temp Cycle	.34	2 Cycles,4 C/min, 122 C range
Rand Vib		.63	6 gRMS,10 min in 1 axis
Pre ATP	Temp Cycle	.34	2 cycles, 4 C/min, 122 C range
ATP	Temp Cycle	.57	4 cycles, 4 C/min, 122 C range
Rand Vib		.35	5.5 gRMS,5 min each of 3 axis

Notes:

Temp Cycle = Temperature Cycling
Rand Vib = Random Vibration
ATP = Acceptance Test Procedure

Figure 2.1 EQUIPMENT A SCREENING PROGRAM

Test Level	Environment	Precipitation Efficiency	Stress Parameters
Card-Module System	none		
	Temp Cycle	.82	8 cycles, 4 C/min, 125 C range
	Rand Vib	.64	6.1 gRMS,10 min
	Temp Cycle	.97	17 Cycles,4 C/min, 125C range
	Sine Vib	.01	2.2 g, 20 min
	Temp Cycle	.96	15cycles, 4 C/min, 125 C range
	Sine Vib	.01	2.2 g, 20 min

Notes:

Temp Cycle = Temperature Cycling
Rand Vib = Random Vibration
Sine Vib = Sine Vibration

Figure 2.2 EQUIPMENT B SCREENING PROGRAM

Test Level	Environment	Precipitation Efficiency	Stress Parameters
Card-Module	Temp Cycle	.99	30 cycles,15C/min, 140C range
System			
	Temp Cycle	.86	10 cycles, 4 C/min, 110 C range
	Rand Vib	.63	6 gRMS, 10 min

Notes:

Temp Cycle = Temperature Cycling
Rand Vib = Random Vibration

FIGURE 2.3 EQUIPMENT C SCREENING PROGRAM

PART TYPE	RELIABILITY GRADE	
MICROCIRCUITS	B	B1
	286	256
SEMICONDUCTORS	TXV	JAN
Transistors	147	97
Diodes	302	34
PASSIVES	P	MIL
Resistors	1191	25
Capacitors	663	17
OTHERS	MIL	MIL EQUIV
Magnetics	5	12
Relays	42	0
Connectors	42	0
PWB	28	0
CONNECTIONS		
Hand	1340	
Wave solder	21900	
Wire Wrap	1250	

FIGURE 2.4 PARTS and WORKMANSHIP COMPLEXITY of EQUIPMENT A

PART TYPE	RELIABILITY GRADE	
MICROCIRCUITS	B0	B1
	438	480
SEMICONDUCTORS	TXV	JAN
Transistors	105	18
Diodes	220	4
PASSIVES	P	MIL
Resistors	1350	16
Capacitors	935	11
OTHERS	MIL	MIL EQUIV
Magnetics	34	28
Relays	1	0
Connectors	36	4
PWB	23	0
CONNECTIONS		
Wave solder	20555	

FIGURE 2.5 PARTS and WORKMANSHIP COMPLEXITY of EQUIPMENT B,MDI

PART TYPE	RELIABILITY GRADE	
MICROCIRCUITS	B0	B1
	57	72
SEMICONDUCTORS	TXV	JAN
Transistors	74	10
Diodes	170	8
PASSIVES	P	MIL
Resistors	881	2
Capacitors	412	10
OTHERS	MIL	MIL EQUIV
Magnetics	14	36
Relays	2	0
Connectors	27	0
PWB	14	0
CONNECTIONS		
Wave solder	6724	

FIGURE 2.6 PARTS and WORKMANSHIP COMPLEXITY of EQUIPMENT B ,MDRI

PART TYPE	RELIABILITY GRADE	
MICROCIRCUITS	B0	B1
	170	174
SEMICONDUCTORS	TXV	JAN
Transistors	105	19
Diodes	312	10
PASSIVES	P	MIL
Resistors	1474	3
Capacitors	786	14
OTHERS	MIL	MIL EQUIV
Magnetics	40	55
Relays	4	0
Connectors	39	4
PWB	20	0
CONNECTIONS		
Hand	35	
Wave solder	13106	

FIGURE 2.7 PARTS and WORKMANSHIP COMPLEXITY of EQUIPMENT B, HUD

PART TYPE	RELIABILITY GRADE		
MICROCIRCUITS	B0	B1	
	2	425	
SEMICONDUCTORS	TXV	JAN	
Transistors	192	57	
Diodes	205	34	
PASSIVES	P	M	MIL
Resistors	643	888	79
Capacitors	840	12	24
OTHERS	MIL	MIL EQUIV	
Magnetics	2	30	
Relays	3	0	
Connectors	2	53	
PWB	15		
CONNECTIONS			
Hand	132		
Wave solder	12729		

FIGURE 2.8 PARTS and WORKMANSHIP COMPLEXITY of EQUIPMENT C

Although the prediction of factory defect densities and fallout are of major interest to the HDBK user, the HDBK does not currently have the methodology or data base necessary to perform the required calculations. The handbook recognizes that the defect density is related to the stress level and therefore has defect densities for the various application environments eg., AIF, ML etc. The problem is that factory ESS has stress levels different than the environments covered in the tables and further, the factory ESS is not necessarily directly related to the field stress levels. The objective is to stimulate not simulate two different field environments could conceivably have the same factory ESS program. This deficiency and proposed solutions are discussed in 2.5.

The results of these calculations are provided in Table 2.1 for a selection of different application environments.

2.3.1.3 Step 3, Determine Defects Removed and Remaining. The defects removed by ESS, i.e., factory fallout were estimated by multiplying the defects per system determined in 2.3.1.2 by the screening strength of each ESS as determined from 2.3.1.1. Defects escaping one screen carried over for subsequent screens.

As a result of the calculations, the total latent defects, and the detected and undetected patent defects, were calculated for each assembly test level. Yields were then calculated from the defects removed based on a Poisson distribution i.e. Yield = EXP (- Detected Patent Defects).

TABLE 2.1 Predicted Defects PER SYSTEM.

SYSTEM	PREDICTED DEFECTS PER SYSTEM BASED ON CURRENT DOD-HDBK-344								
	AIF			ML			CL		
	TOTAL	% PARTS	% WRK	TOTAL	% PARTS	% WRK	TOTAL	% PARTS	% WRK
Equip-ment A	.95	81	20	2.7	77	22	31.9	68	32
MDI	.70	93	7	2.04	92	8	32.9	92	8
MDRI	1.59	97	3	1.9	97	3	21.2	95	5
HUD	.91	96	4	2.86	94	4	36.6	95	5
Equip-ment C	1.09	96	4	2.95	95	5	32.7	93	8

2.4 Collection of Observed Factory Defect Data. Prior to this study contract, LSL had developed an extensive and computerized Failure Reporting, Analysis, and Corrective Action system (FRACAS) and data base that contained test and failure data on the three equipment selections. An established data base of actual production failures was thus available for this project and was used to compare the actual factory results with the HDBK predictions for both defect density and screening strength. This section describes the collection and preliminary analysis of this data.

2.4.1 System Level Data. The system level removal data were analyzed to determine the nature and cause of the test discrepancy; thus, for system test level, it was possible to distinguish between "removals" and actual defects and to also identify the probable cause eg part,workmanship, design etc. This review constituted a "preliminary" review as described in 4.5.3 of the proposed HDBK (see Appendix B) and was performed in advance of detailed root cause physics of failure analyses. Detailed analyses were performed when problems and out of control conditions were identified.

The need for detailed analysis was determined by comparing actual results with established requirements and expectations that were directly relatable to reliability and cost requirements. The method logy used by LSL for determining the need for detailed analyses has been included in the recommended revisions to the HDBK. Because of the available data, it was possible to conduct part of the study contract analyses by writing special software to extract the data from FRACAS that was pertinent to the ESS analysis. The scope of this study contract did not allow for additional root cause failure analysis.

2.4.2 Presystem Level Data. Although all presystem level test and failure data were also recorded in FRACAS, the preliminary review that was performed on system level discrepancies was only performed at assembly and module level when trends and potential problems were indicated. Thus, the data base for lower level contained a mixture of defect, as well as repair and removal data. Patent and latent defects were thus included with patent-error defects as well as induced and diagnostic removals etc. Since data in this form was not directly suitable for ESS analysis purposes, some method of extracting latent defects was required. Because of the high reliability emphasis on the Equipment A program, extensive analysis of preassembly removals and defects had been performed over several years. This data was used to provide a statistical inference as to what percentage of assembly removals were likely to be latent defects. This factor was then applied to the raw assembly level data to estimate the number of latent defects on all three programs.

The primary need for lower level data was to assess assembly level ESS effectiveness and also to estimate and validate the defect density estimates for the various commodity-reliability grades. The error introduced by the use of a factor to determine assembly level latent defects from removal data was considered in the analysis process and was not believed to be consequential to the results and conclusions. Where the results could have affected the HDBK accuracy, the appropriate parameter was indicated as being "user-definable" and provided as a "suggested value" in the HDBK revisions.

2.5 Analysis of observed Predicted Results. This section compares the HDBK predictions for defect density and screening strength with the observed results and discusses recommended changes to the ESS methodology. The analysis addresses defect density in 2.5.1 and screening strength in 2.5.2.

2.5.1 Comparison of observed and estimated defects. The observed factory defects from system level ESS are compared with the HDBK estimates in Table 2.2 and 2.3. Recall that since the HDBK did not have a methodology or data base for predicting factory ESS defect densities, the predictions were made for several environments. The selection of the particular environments for these tables was not based on the eventual application of the equipment, since this has no meaning for factory ESS, but because they provided the closest correlation with actual results, and would thus be useful for rescaling purposes.

The inability to predict factory defect levels represents a major modeling problem that must be corrected to have a viable ESS methodology. The recommendation for correcting this was to rescale the HDBK tables to create a reference for factory ESS. Since defects are a function of stress level, as indicated by including the various environmental conditions in the HDBK tables, a stress adjustment factor is also required to modify the factory estimate. However, before addressing this problem an additional fundamental problem had to be addressed. The proportions of workmanship and parts defects in the observed data did not correlate with the HDBK predicted proportions. The problem was addressed by analysing workmanship and part defect density estimates separately.

TABLE 2.2 Observed Defects Per System

SYSTEM	OBSERVED DEFECTS PER SYSTEM (SYSTEM LEVEL TESTING)				
	TOTAL	PARTS	WORKMANSHIP	% PARTS	% WORKMANSHIP
Equipment A	1.44	1.09	.35	76	24
Equipment B					
MDI	2.45	1.82	.63	74	26
MDRI	1.18	.86	.32	73	27
HUD	1.52	1.02	.5	67	33
Equipment C	2.54	2.11	.43	83	17

PREDICTED DEFECTS

SYSTEM	PREDICTED DEFECTS PER SYSTEM								
	AIF			ML			CL		
	TOTAL	% PARTS	% WRK	TOTAL	% PARTS	% WRK	TOTAL	% PARTS	% WRK
Equipment A	.95	81	20	2.7	77	22	31.9	68	32
Equipment B MDI	.70	93	7	2.04	92	8	32.9	92	8
MDRI	1.59	97	3	1.9	97	3	21.2	95	5
HUD	.91	96	4	2.86	94	4	36.6	95	5
Equipment C	1.09	96	4	2.95	95	5	32.7	93	8

TABLE 2.3 Comparison of Predicted and Observed Defects Per System

OBSERVED DEFECTS PER SYSTEM	PREDICTED DEFECTS PER SYSTEM AIF ENVIRONMENT		PREDICTED DEFECTS PER SYSTEM ML ENVIRONMENT	
	PREDICTED DEFECTS PER SYSTEM	PREDIC-TION ERROR	PREDICTED DEFECTS PER SYSTEM	PREDIC-TION ERROR
1.44	0.95	-52%	2.7	47%
2.45	0.7	-250%	2.04	-20%
1.18	1.59	26%	1.9	38%
1.52	0.91	-67%	2.86	47%
2.54	1.09	-133%	2.95	14%

i) Analysis and recommendations for predicting workmanship defects

The error between the predicted and observed defects per system is shown in Table 2.3. The prediction error was not consistent across all equipment types for either the AIF or ML environments, thus indicating there was a fundamental prediction problem other than rescaling the handbook tables. Examination of the data in Table 2.2 showed an inconsistency in the proportion of workmanship and parts related defects. Subsequent analysis revealed that the discrepancy was due primarily to the estimate of workmanship defects.

The observed fractions of parts and workmanship defects for Equipment A were 76% parts 24% workmanship and compared favourably with the 77% parts 23% workmanship predicted for ML.
The same proportions for Equipment B were 70% parts, 30% workmanship observed vs. 95% parts, 5% workmanship predicted. For Equipment C, the values were 83% parts 17% workmanship observed, compared with 95% parts, 5% workmanship predicted. The predictions for both Equipment B and Equipment C were thus unsatisfactory.

A closer examination revealed that workmanship defects, and hence the parts vs. workmanship proportions, were greatly influenced by the number of hand solder connections. This was due to the HDBK defect density factor for hand solder connections being nearly 40 times higher than that for reflow/wave soldering.

Since Equipment A contains a mixture of both flat pack (hence hand solder) and through hole (hence wave soldered) parts, compared with essentially all wave soldered connections on Equipment B and Equipment C, the proportions of workmanship defects appear quite different.

Further error was introduced because the handbook only considered solder connections in the estimate of workmanship defects. In practice, many workmanship faults were related to other factors, for example:

i) lead forming and/or dressing,

ii) insulation stripping,

iii) shorts due to foreign materials,

iv) component mounting and bonding,

v) mechanical handling damage,

vi) electrical (eg. ESD) handling damage,

vii) wire routing,

viii) mechanical assembly eg. torquing,

ix) bending connector pins.

Since there was insufficient data to determine appropriate defect densities for the all of the various workmanship considerations, the recommendation was to use a different methodology for determining workmanship complexity. The recommended approach was to adopt the DOD-STD-2000 methodology for determining assembly and soldering complexity. The approach is described in Appendix C of DOD-STD-2000-1 and in principle determines an assembly normalizing number based on the number of components + leads + terminals + wire + PWB and a soldering normalizing number based on the number of solder connections. Although the purpose for determining these values is different for DOD-STD-2000 than DOD-HBDK-344, (also that DOD-STD-2000 became MIL-STD-2000 during the study program) the means of describing workmanship complexity seemed to be simple and valid. If more industry data becomes available, it would be possible to define workmanship complexity more precisely in terms of the number of individual processes and types; however, in the interim the DOD-STD-2000 approach should be sufficiently accurate for ESS planning purposes.

To establish defect densities for the assembly and soldering normalizing numbers, the observed workmanship defects per system were compared with recalculated normalizing numbers for each of equipments. The defect densities were thus determined to be 28 PPM for the assembly normalizing number and 6 PPM for the soldering normalizing number. Before assessing how appropriate this modeling was, the problem of estimating part defect density still had to be addressed.

b) Analysis and recommendations for part defects. The Equipment A FRACAS data extraction program was modified to provide the capability of determining the defect density of the system level fallout by part type and reliability grade. Using this facility, it was thus possible to determine the defect densities of various commodities and to compare them to the HDBK defect density tables ie HDBK Tables 5.2 - 5.10.

Before making the comparison,it was first necessary to address the problem of not being able the estimate defects and fallout under different and varying stress levels such as occur in factory ESS. The solution to this problem essentially modified the modelling and mathematics to includes a stress adjustment factor (SAF) and defined defects relative to a 'baseline' stress. The SAF factor rescales defects densities defined at this baseline stress to any desired factory ESS or field application. Since the appropriate SAF was not known at this stage in the analysis, the defect densities were compared ratiometrically as a group within one stress level and collectively between two stress levels ie ML application and factory ESS stress levels for Equipment A.

The defect densities from the HDBK tables for an ML application and the observed defect densities were normalized with respect to MIL M 38510 integrated circuits and then compared on a ratiometric basis. The ML environment was selected since it provided a reasonably close correlation with the observed results. The defect density for semiconductors was calculated as a weighted average of the transistor and diode tables. This analysis was designed to disclose any anomalies in the defect density of one part type with respect to the other part types. As can be seen from Table 2.4, the greatest errors occurred on capacitors and magnetics where the error was approaching an order of magnitude. The other part types correlated within a factor of 2. This later degree of correlation was considered satisfactory knowing that the Tables represent a general average and that some spread should be anticipated considering the wide diversity in technologies and vendors within any group. Although based on these findings the HDBK tables for capacitors and magnetics should probably be rescaled, the HDBK revisions recommended in Appendix B, retain the original values (ratiometrically) since the Equipment A data base alone was not considered to be sufficient to make a generalized change.

However, the methodology of the proposed HDBK was changed to allow the user to analyze and use his own data, thereby reducing the need for high accuracy in the HDBK tables and providing the methodology for the user's data to override any anomalies in the HDBK data.

To compare the magnitude of the defect densities, the HDBK defect densities for the ML environment were compared with the observed values. The purpose of this comparison was to determine an appropriate scaling factor for creating a factory ESS defect density table from the HDBK data. As shown by the last column of Table 2.3, the ML environment can be rescaled by 1.15 to create a defect density data base for system level fallout. The factor of 1.15 however is incomplete since it is necessary to model total defects not just system level removals. It is thus necessary to convert system level fallout into total defects by dividing the system level fallout by the screening strength (i.e. to compute total latent defects present at system level) and adding the defects removed at assembly level.

TABLE 2.4. COMPARISON OF OBSERVED AND DOD-HDBK-344 DEFECT DENSITIES FOR PARTS

PART COMMODITY	DOD-HDBK-344 ML PPM	RATIO TO STD IC	EQUIP A FACTORY DATA 1987 & 1988 PPM	RATIO TO STD IC	HDBK-344 ADJUSTMENT FACTOR
STD IC	139	1.0	194	1.0	1.40
NON STD IC	279	2.0	587	3.0	2.10
STD SEMI	220	1.6	164	0.8	0.74
NON STD SEMI	881	6.3	1178	6.1	1.34
RESISTORS	54	0.4	116	0.6	2.16
CAPACITORS	415	3.0	70	0.4	0.17
MAGNETICS	5643	40.6	767	4.0	0.14
				AVG.	1.15

The fallout from assembly level ESS on Equipment A was reviewed to determine the removal rates for parts, and workmanship defects and errors. (To understand and appreciate these defect definitions and the importance in separating latent and patent-error defects, the reader is referred to Appendix A). The root cause failure analysis data in FRACAS was then used to determine the ratio of latent defects to removals and errors. The results indicated that approximately 25% of the reported removals at system level where actually caused by latent defects. Considering these factors and the estimated system level screening strength, the rescaling factor was estimated as being 1.5. Since the Equipment A ESS Stress levels (not necessarily duration) were sufficiently close to the R&M 2000 stress level guidelines, the defect densities for factory ESS were consistent with R&M 2000 guidelines were determined by rescaling the ML defect densities found in the HDBK Tables 5.2 through 5.10 by the 1.5x factor.

c) Conclusions concerning the changes to defect density modelling and tables. The final task in the analysis and recommendations concerning defect densities was to recompute the predicted defect fallout based on the modelling and defect density table changes described above and to compare these results to the actuals for the three equipment types. The comparison was made for both the estimate of total, part , and workmanship related defects. The effect that the limited sample size, ie number of systems produced had on the observed results was also considered . The observed mean can be expected to be different than the actual mean defect density because of statistical variation. This variation was calculated from the standard error of the mean, assuming the defects were Poisson distributed. The results of the comparison are given in Table 2.5. The upper part of the table compares the magnitude of the predicted and observed total defects. This suggests the predicted results were within 20% of the observed values and within 1 to 2 standard deviations of the statistically expected error . The average error across 5 equipments was 1.2%. The middle part of the table compares the parts defects per system. This indicates that the estimate for part defects was within 30% with an average error of 0.0%. The lower part of the table compares the estimated and observed workmanship defects. The error is effectively within 31% with an average of 0.0% across the 5 equipments. The recommended changes to the HDBK thus appear to have improved the accuracy problems encountered with the current handbook. The simplified workmanship complexity definition based upon DOD STD 2000 also seems to be sufficiently accurate for planning purposes.

Table 2.5 Comparison of Observed and Predicted Defects per System.

TOTAL DEFECTS PER SYSTEM

EQUIPMENT TYPE	PREDICTED DEF/SYS (REVISED HDBK)	OBSERVED DEFECTS DEF/SYS SYS ALL LEVELS		PREDICTION ERROR	STANDARD ERROR OF MEAN
Equipment A	2.4	1.44	2.16	10%	4%
Equipment B					
MDI	2.31	2.45	2.45	-6%	14%
MDRI	1.03	1.18	1.18	-14%	11%
HUD	1.91	1.52	1.52	20%	12%
Equipment C	3.67	2.54	3.81 AVG.	-4% 1.2%	4%

WORKMANSHIP DEFECTS PER SYSTEM

EQUIPMENT TYPE	PREDICTED DEF/SYS (REVISED HDBK)	OBSERVED DEFECTS DEF/SYS ALL LEVELS	PREDICTION ERROR	STANDARD ERROR OF MEAN
Equipment A	0.714	0.518	27%	8.2%
Equipment B				
MDI	0.783	.637	19%	27.5%
MDRI	0.243	.319	-31%	21.2%
HUD	0.510	0.502	2%	20.9%
Equipment C	0.555	0.648 AVG.	-17% 0.0%	9.7%

PARTS DEFECTS PER SYSTEM

EQUIPMENT TYPE	PREDICTED DEF/SYS (REVISED HDBK)	OBSERVED DEFECTS DEF/SYS ALL LEVELS	PREDICTION ERROR	STANDARD ERROR OF MEAN
Equipment A	1.68	1.642	2%	5%
Equipment B				
MDI	1.52	1.813	-19%	16%
MDRI	0.79	0.861	-9%	13%
HUD	1.4	.018	27%	15%
Equipment C	3.12	.162 AVG.	-1% 0.0%	4%

① LATENT DEF ESTIMATED AS SYSTEM DEF X 1.5 FOR EQUIP A AND C BECAUSE OF ASSY T/C SCREENING, LATENT DEFECTS = SYSTEM DEFECTS FOR [MDI, MDRI, HUD, i.e., NO ASSY SCREENING]

② PREDICTION ERROR = (Predicted/Actual-1)100%

③ STANDARD ERROR OF MEAN DUE TO LIMITED SAMPLE SIZE, CALCULATED ASSUMING A POISSON DIST., i.e., δ = SQUARE ROOT OF (DEFECTS PER SYSTEM/SYSTEMS PRODUCED) EXPRESSED AS A PERCENTAGE OF THE MEAN.

2.5.2 Analysis of Observed and Predicted Screening Strength. The basic definition of screening strength SS (as suggested in 2.2.2 above) is the fraction of latent defects precipitated and removed by a screen. Screening strength is thus the product of a precipitation efficiency term and a detection efficiency term. In order to measure the screening strength of the actual factory ESS programs used on the three equipment selections, the effects of precipitation and detection need to be individually measured and assessed. Further, to be able to compute SS both the latent defects removed and the total latent defects present need to be determined. Although it is possible to separate the fallout into errors and defects by performing a preliminary analysis (as is done in the LSL FRACAS system), it would still be necessary to distinguish between patent defects escaping from a previous screen and those precipitated by the screen being analyzed. Also, the total latent population can not be determined until all latent defects have been removed. This would require extensive factory and field data to be collected and analyzed to separate latent defects from induced defects and from the defects expected when the equipment has reached the screening limit (ie constant failure rate). Even then the appropriate value for total latent defects would still not be known because of the (probable) effect that latent defects are a function of the stress level and thus the change in stress between factory and field could significantly affect the perceived total. Performing tests before and after a screen as well as performing 100% analysis to root cause would be useful in an overall study contract and could help the problem of determining escaping patent defects, but both represent an undesirable and unwarranted production expense and were beyond the scope of this contract. Further, performing these tests and analyses would not have addressed the problem of being able to determine the total latent defects. Some method of being able to measure the screening strength needed to be devised.

The approach adopted for the study was to curve fit the production data to a theoretically expected expression and, provided the data were reasonably well represented by the solution,extract the required information on screening strength from the curvefitting parameters. The underlying theory and approach taken are discussed in Appendix A. To perform the analysis care must taken in the treatment of the different types of defects ie it is vital that errors be distinguished from defects and that defects are considered as latent, patent and a function of applied stress. The analysis must also be aware of the convoluted effects of defect precipitation and detection. To analyze the data, it was necessary to curvefit various combinations of data to determine the distribution in normalized defects eg DPM or DPU with respect to stress duration eg time or cycles. These analyses were performed using specially developed software and curve fitting the observed results to the following expression.

$$D_{REMOVED} = D_{E1}D_P(1 - e^{-B_1 t}) + D_{E2}D_I\left[1 - \frac{B_2}{B_2 - A}e^{-At} - \frac{A}{A - B_2}e^{-B_2 t}\right]$$

$$+ \frac{D_{E3}D_C}{B_3}[e^{-B_3 t} + B_3 t - 1] \qquad (2\text{-}1)$$

D_p = EXISTING PATENT DEFECTS AT START OF ESS

D_I = LATENT DEFECTS AT START OF TEST

D_c = LIMITING I.E. CONSTANT FAILURE RATE'

D_E = TEST DETECTION EFFICIENCIES

Б = TEST DETECTION EFFICIENCY 'K' FACTOR (S)

A = ESS DEFECT PRECIPITATION 'K' FACTOR

This equation has 3 distinct terms representing the:

a) detection of previously precipitated latent defects
b) detection of latent defects precipitating during ESS.
c) detection of defects precipitating at a constant rate i.e., determined by the limiting MTBF.

These three terms and the combined defect removal rate are illustrated in Figure 2.9.

The detection of precipitating defects has within itself two exponential terms, one due to precipitation efficiency and the other due to detection efficiency.

The perceived effect of precipitation efficiency and detection efficiency depends upon the relative 'K' factors of these terms and is illustrated in Figure 2.10.

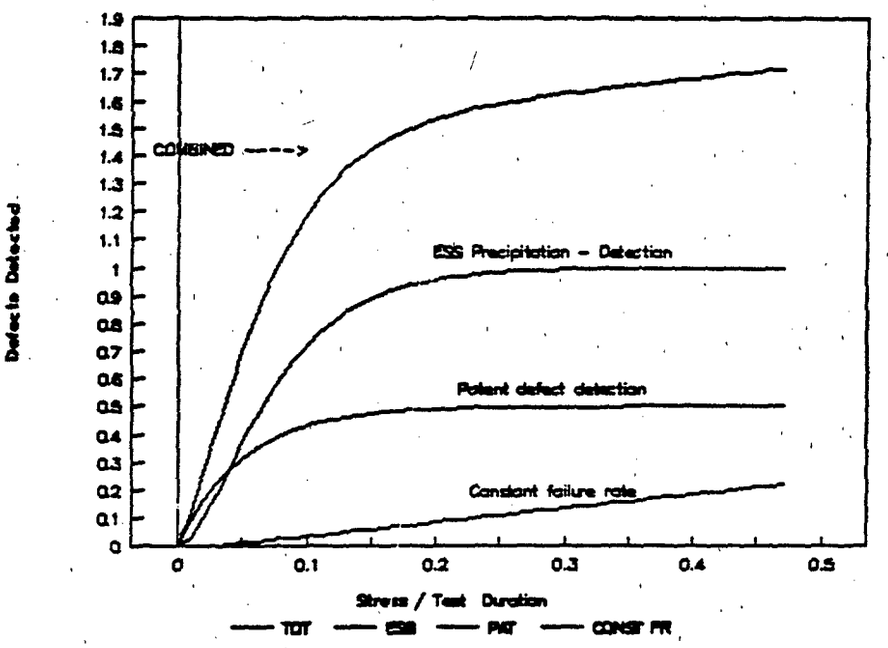


FIGURE 2.9 ESS Model.

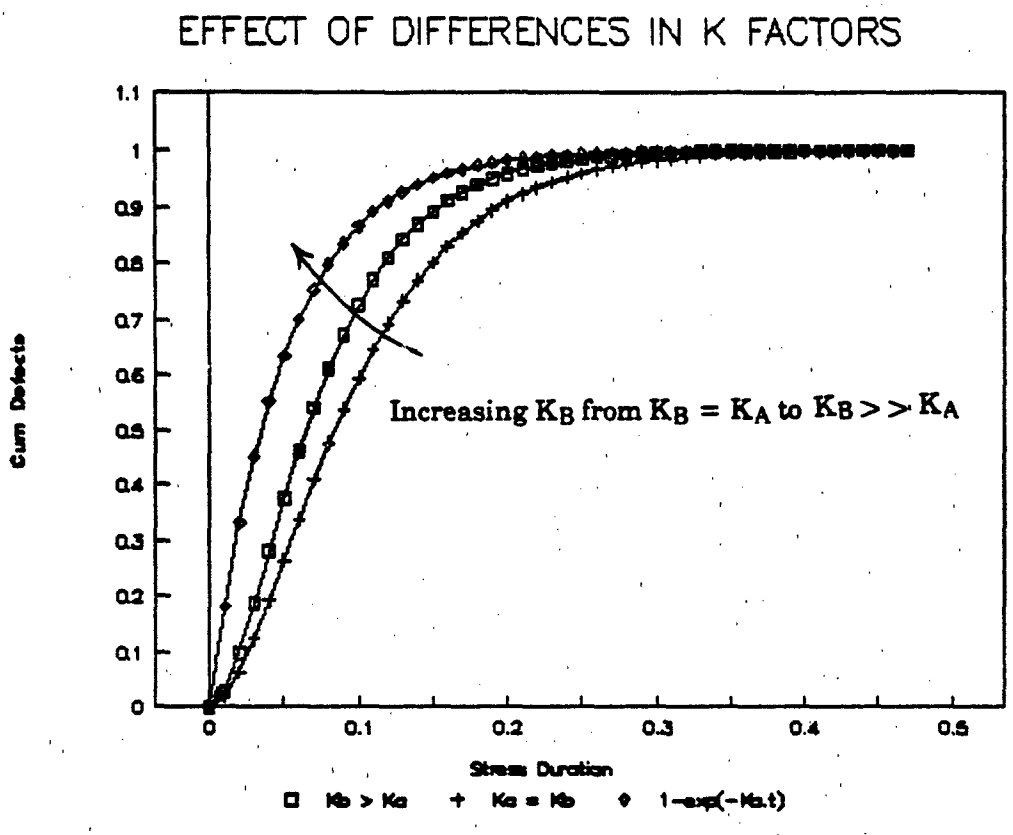


FIGURE 2.10 Defect Distribution for Different 'K' Factors.

If the K factors are different, the result is a nearly exponential distribution that is dominated by the smaller 'K'. If, for example, test detection is 'weaker' than defect precipitation, the measured screening strength will actually be the test detection efficiency. In many instances, i.e., when there is a significant difference in K factors the general expression can be simplified to

$$D_{REMOVED} = \left[D_P + D_i(1 - e^{-kt}) + D_c t \right] D_E \qquad (2\text{-}2)$$

where K is the lesser of Ka and Kb and D_E is the detection efficiency (assumed equal for all 3 terms).

The methodology used by LSL, and discussed herein, was to curve fit actual test data to the theoretical expression given above.

With this method, the total latent defect population, escaping patent defects, defects due to a constant failure rate (CFR), and screening strength (precipitation efficiency) i.e., K can all be measured. Note that if the K is dominated by precipitation effects, the detection efficiency (DE) has the effect of a scaling factor and does affect the general shape of the curve. Thus, even though DE may not be known, the curvefitting methodology is still valid for determining K and thus the precipitation effectiveness.

By isolating on a particular environment, eg. T/C, this method also determines the interaction among screening environments and since escaping patent defects are measured, it is also possible to estimate test detection efficiency (partial factor). Since detection efficiency is unique to a specific program which precipitation efficiency is generic, only the precipitation efficiency was of interest for the study and is addressed in this report.

For the analysis, only parts and workmanship defects were used with defects caused by designs, etc., excluded to avoid possible distortion of the results. The results of the analysis are discussed in a,b,c, and d following.

a) Analysis of Equipment A Factory Test Data. Equipment A ESS test flow is described in Part A and Figure 2.1 and consists of temperature cycling interspersed with random vibration. Slight changes to the ESS were made over the course of the study and are reflected in the analysis. The distribution of Equipment A defects as a function of elapsed time is shown in Figure 2.11.

This curve is of initial interest in that it curve fits to the exponential distribution that is fundamental for ESS. This exponential distribution was also confirmed on the detailed analysis discussed in the following.

This distribution of defects is broken down into more detail in Figure 2.12, wherein the defects removed at each test are indicated. Temperature cycling defects are annotated by 'T' and random vibration defects are annotated by 'R'. The elapsed time was synthesized from the test duration.

The distribution of defects detected during environmental testing, i.e., temperature cycling and random vibration as opposed to ambient testing is shown in Figure 2.13 against temperature transitions.

If the defects due to random vibration are excluded, the distribution of TC defects is as shown in Figure 2.14. The analysis results, as indicated in the figure are:

i) total population of temp cycle defects = .82 of which .80 are latent and .02 are patent

ii) screening strength of a temperature transition (i.e. 3/4 of temperature cycle) = .156
i.e. $SS = 1-Exp(-Kt)$ where $K = .17, t = 1$
and the screening strength of 1 complete cycle ($t = 4/3$) is thus = .288

iii) the limiting MTBF (during T/C) is 2500. (Note that additional data beyond that available would be required to establish this value with reasonable certainty and that the measured value for limiting MTBF is also for the higher stress levels of factory ESS and is thus a lower value that would be experienced in the field.

A significant observation is that R/V defect removal has not perturbed the curve; thus, indicating

i) RV Defects are from a separate defect population than the TC defects

ii) TC subsequent to RV does not screen or detect additional defects.

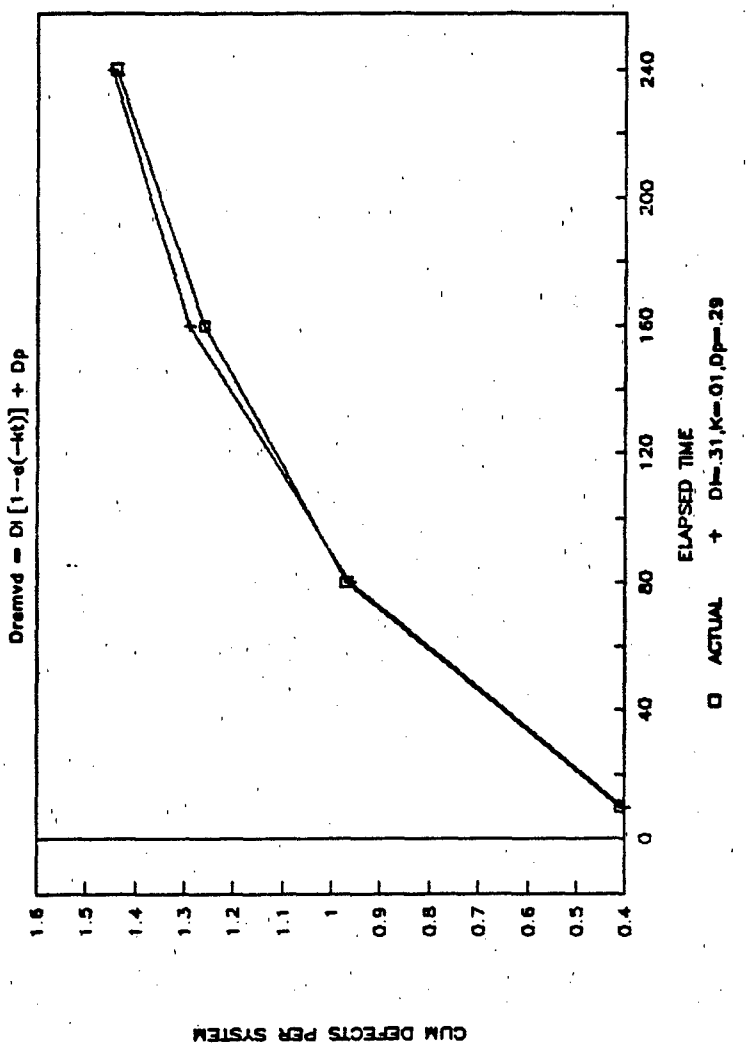


FIGURE 2.11 Equipment A Defect Distribution.

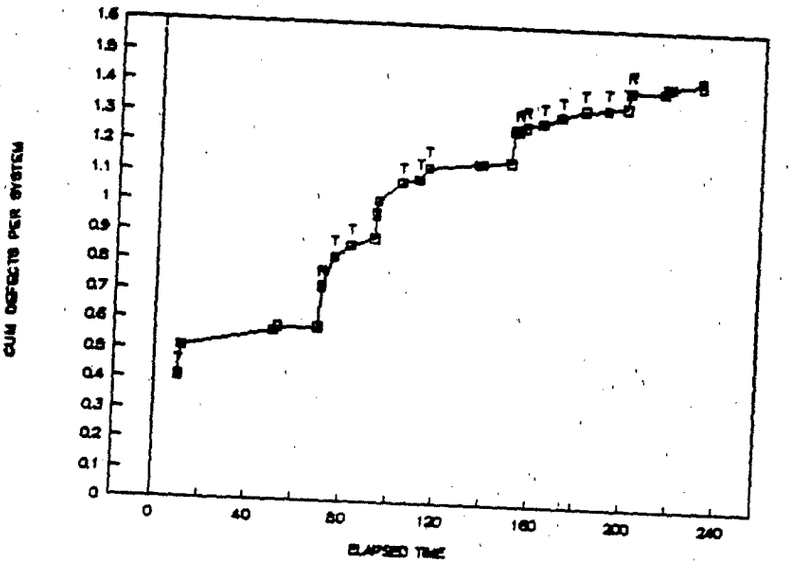


FIGURE 2.12 Equipment A System Level Defects vs. Stress Type.

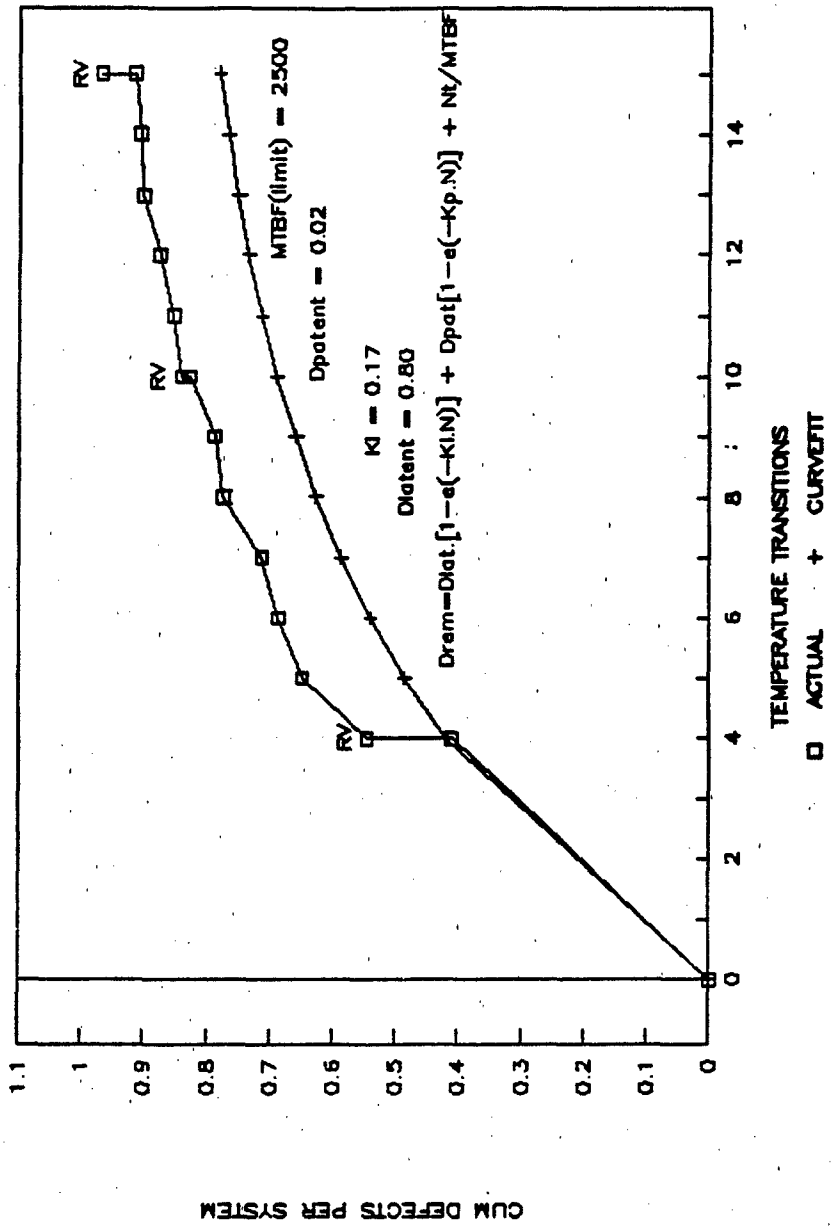


FIGURE 2.13 Equipment A Combined Temp Cycle and RV Defect Distribution.

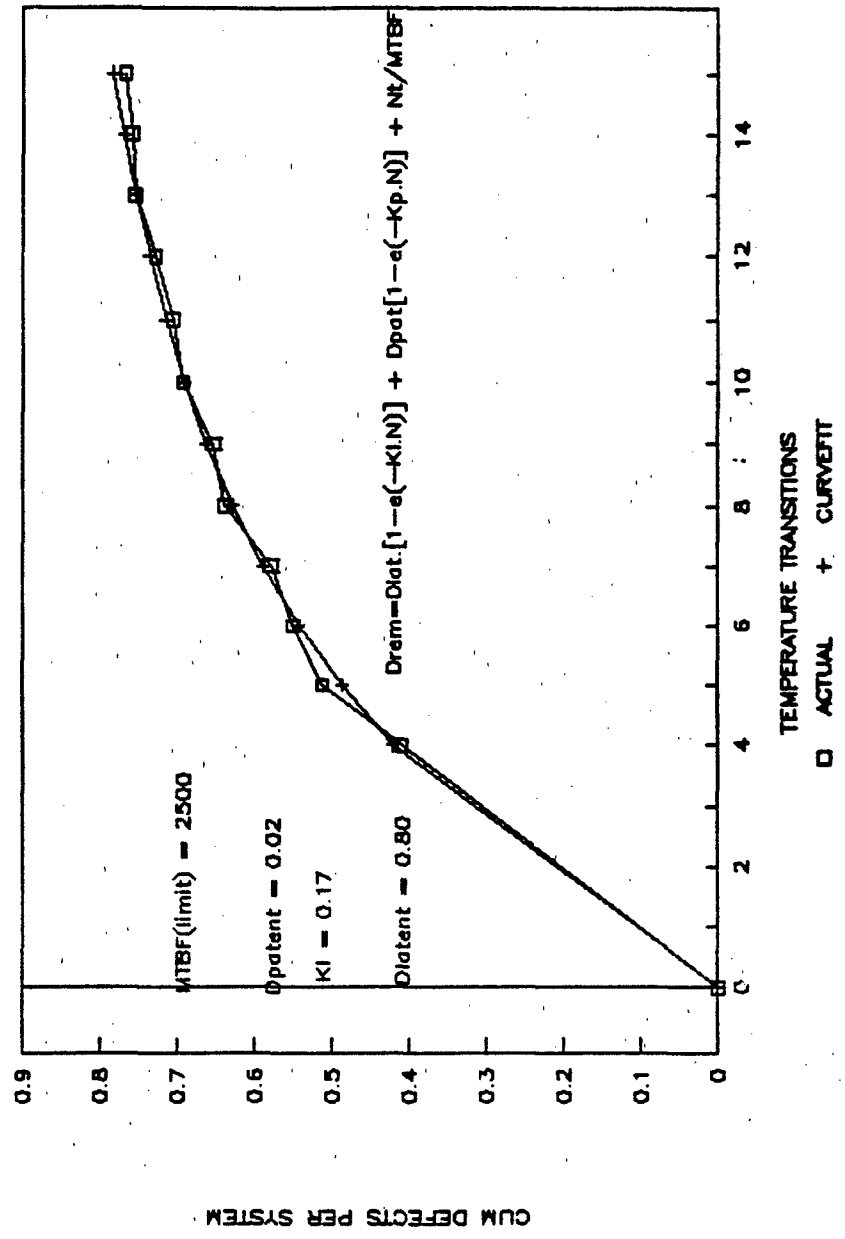


FIGURE 2.14 Equipment A TC Defect Distribution 1987.

These observations are made on the basis that had there been an RV-TC interaction, there would be a marked point of inflexure on the TC defect distribution curve.

The distribution of defects detected during RV, in isolation, is shown in Figure 2.15.

Conclusions from this data are:

i) latent (RV) defect population = .3

ii) screening strength of RV (5 min., 5.5 grms) = .33 in the sensitive axis (i.e. 1-Exp(-Kt), where K = .08, t = 5)

iii) RV in the non sensitive axis (i.e., perpendicular to the plane of the boards) is not effective as evidenced by the lack of removals for Y and Z RV axes.

Combining the TC and RV results indicated that the total TC and RV defect population was 0.82 + 0.3 = 1.12 defects and that RV sensitive defects accounted for .3/1.12 or 27% of the total.

Equipment A data for a different time frame was also analyzed and the results are provided in Figures 2.16 through 2.17. The comparison of the results for the different time frames is discussed in d along with the results for equipment B and C.

b) Equipment B Screening Strength Analysis. The contractually imposed Equipment B test flow is described in Part A and Figure 2.2, and consists of random vibration followed by a succession of temperature cycling plus sine vibration screens.

Whereas the Equipment A test flow consisted of sequences of temperature cycling (T/C) interposed with random vibration (RV), the Equipment B flow, subsequent to RV, is primarily continuous temperature cycling (assuming a negligible screening contribution from sine vibration). The test flow is thus useful in being able to study T/C defect precipitation but has limited use for studying RV defect precipitation.

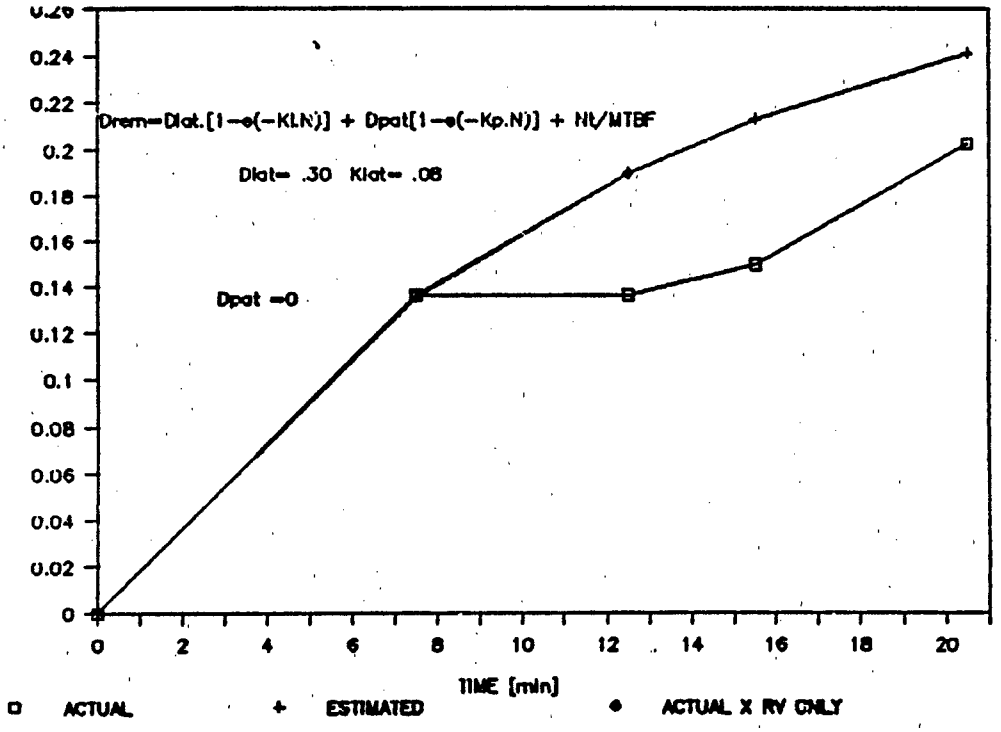


FIGURE 2.15 Equipment A RV Defect Distribution, 1987.

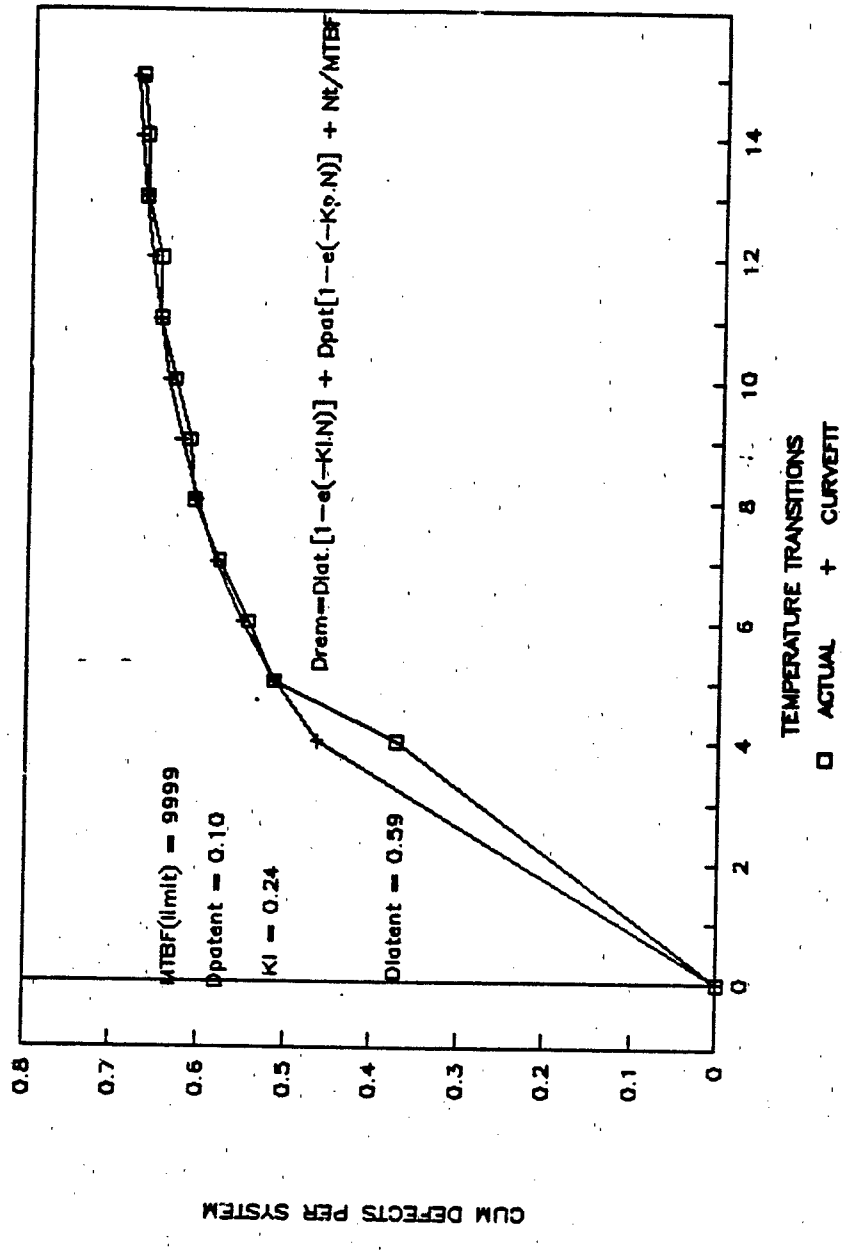


FIGURE 2.16 Equipment A Temp Cycle Defect Distribution, 1988.

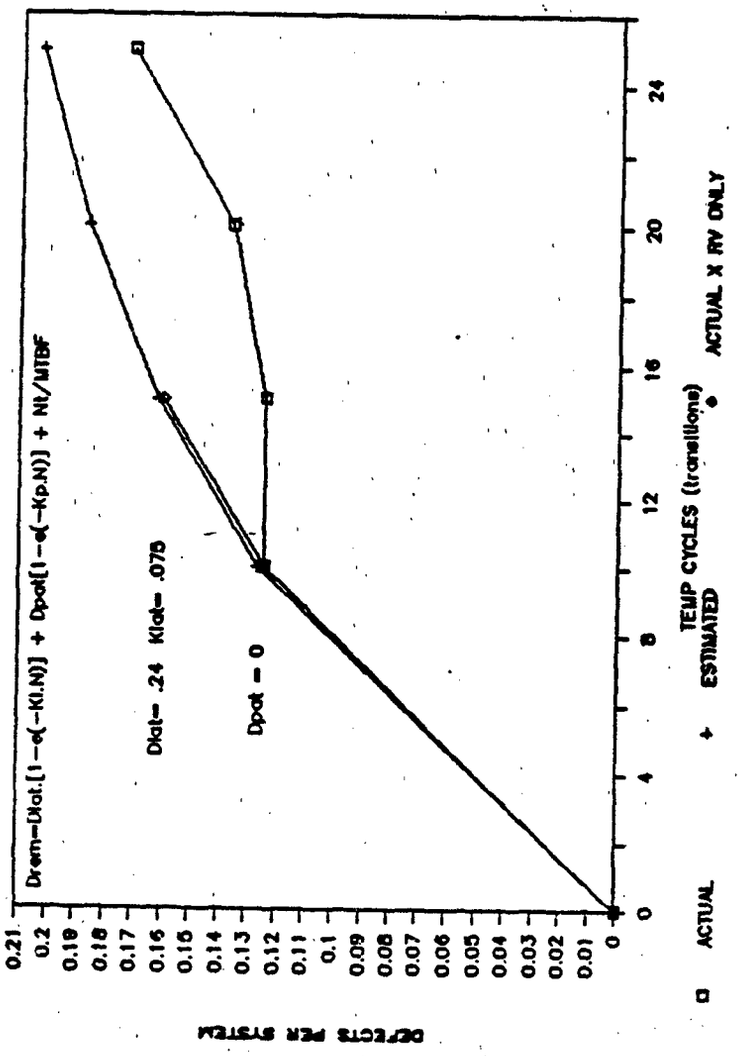


FIGURE 2.17 Equipment A RV Defect Distribution, 1988.

Using analysis techniques described above, the cumulative defect distributions for Equipment B are provided in Figures 2.18 through 2.19.

The data analysis is similar to Equipment A and will be discussed in c following.

c) Equipment C Screening Strength Analysis. The test flow for Equipment d was previously described in Part A and Figure 2.3, and consisted of temperature cycling interposed with one RV sequence.

The test flow can thus be analyzed to determine the screening strength of T/C and the interaction between RV and T/C. Since RV is only performed once, the RV screening strength can not be estimated using the curve fitting methodology.
The total defect distribution is provided in Figure 2.20 and can be used to estimate the T/C screening strength.

The 'step' at 5 cycles is due to the effect of RV performed between cycles 5 and 6. The resulting T/C distribution, excluding the RV effect, is shown in Figure 2.20, and can be reasonably modeled by the simplified equation given in 2.5.2.

As was also observed for Equipment A, the removal of RV defects does not result in a distortion of the T/C defect distribution thus indicating that RV and T/C defects belong to different populations:

- RV does not precipitate defects subsequently detected by T/C.

- RV does not remove defects that could be removed by T/C.
- T/C does not remove defects that could be removed by RV.

Equipment C data for a different time frame is presented in Figure 2.21 and shows similar effects.

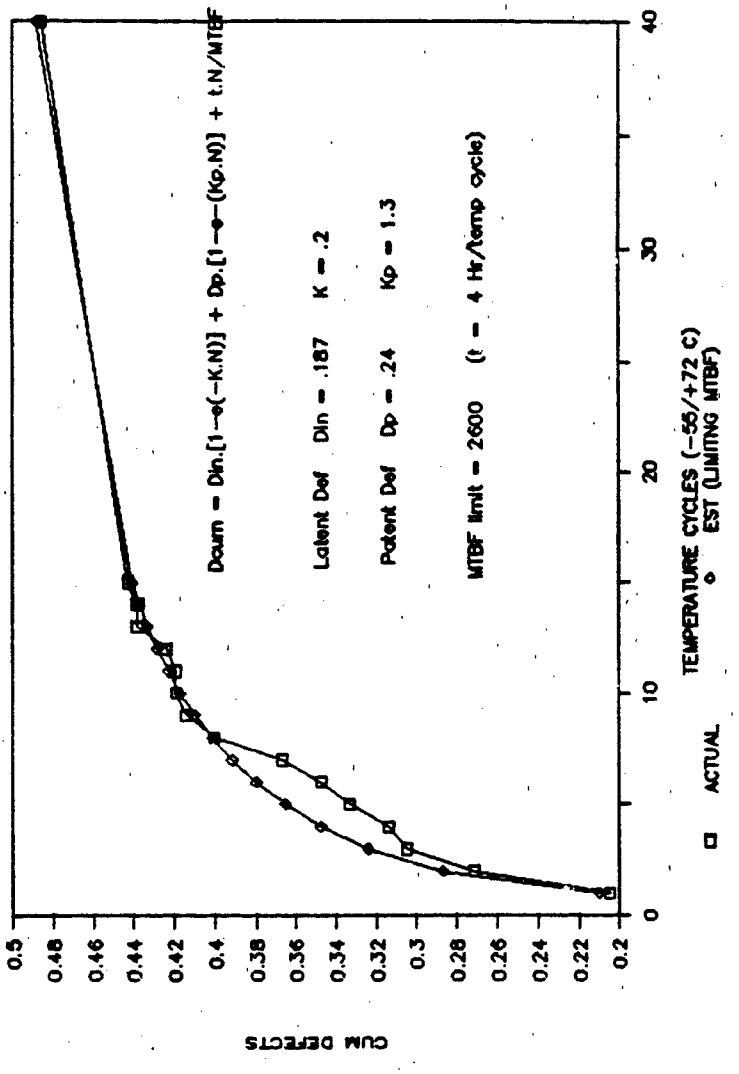


FIGURE 2.18 Equipment B Temp Cycle Defect Distribution 1987.

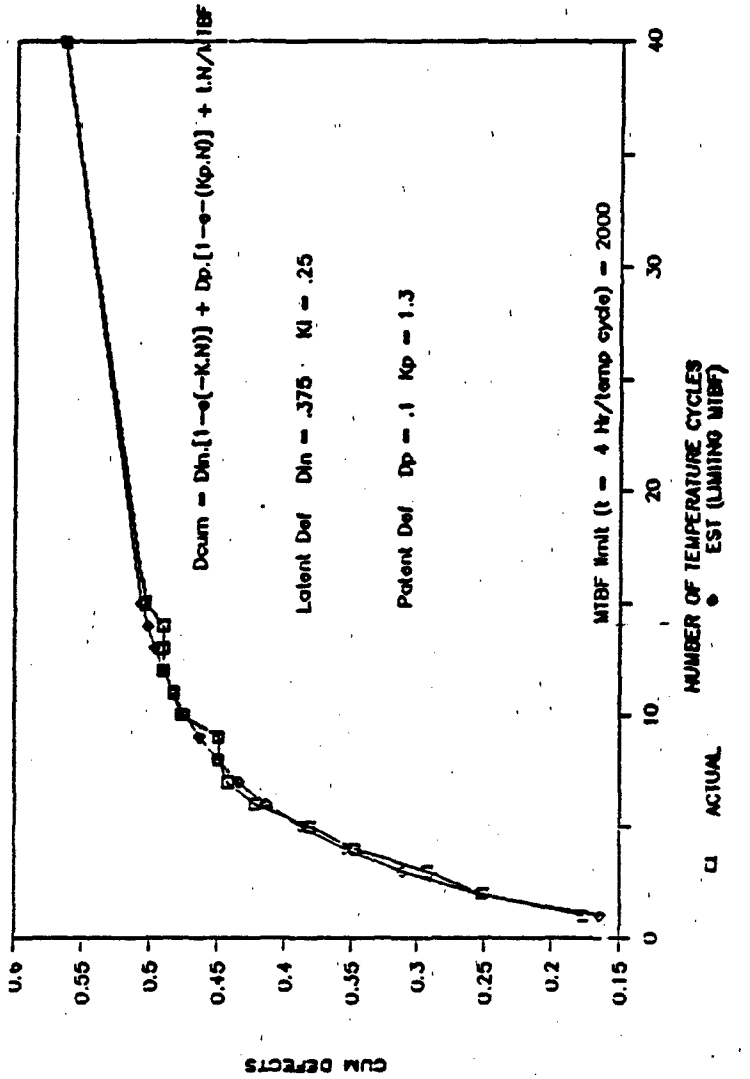


FIGURE 2.19 Equipment B Temp Cycle Defect Distribution 1988.

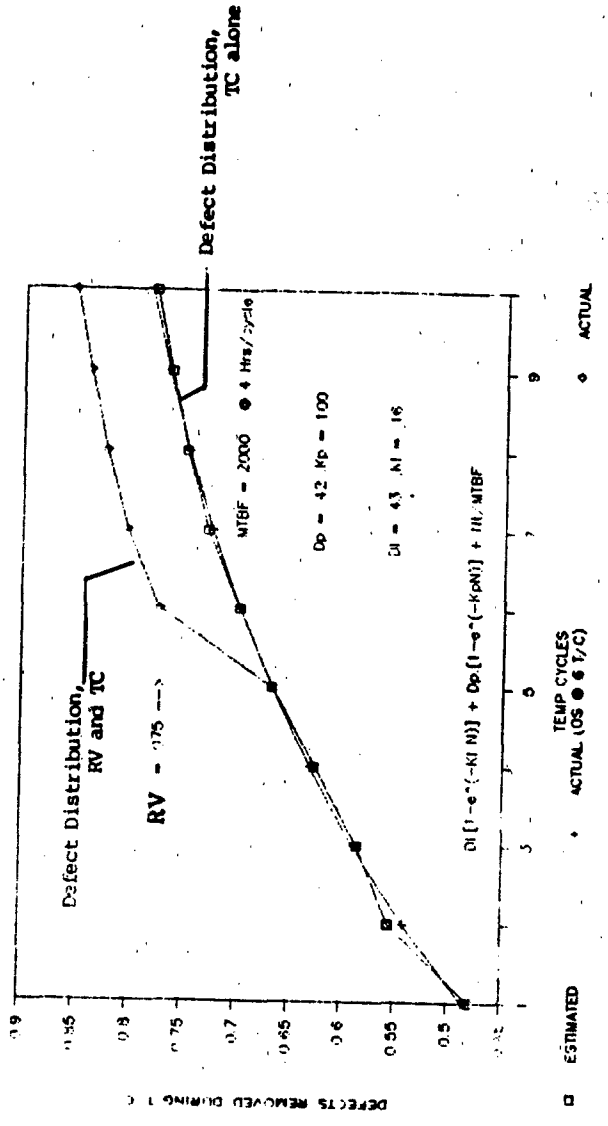


FIGURE 2.20 Equipment C Defect Distribution, 1987.

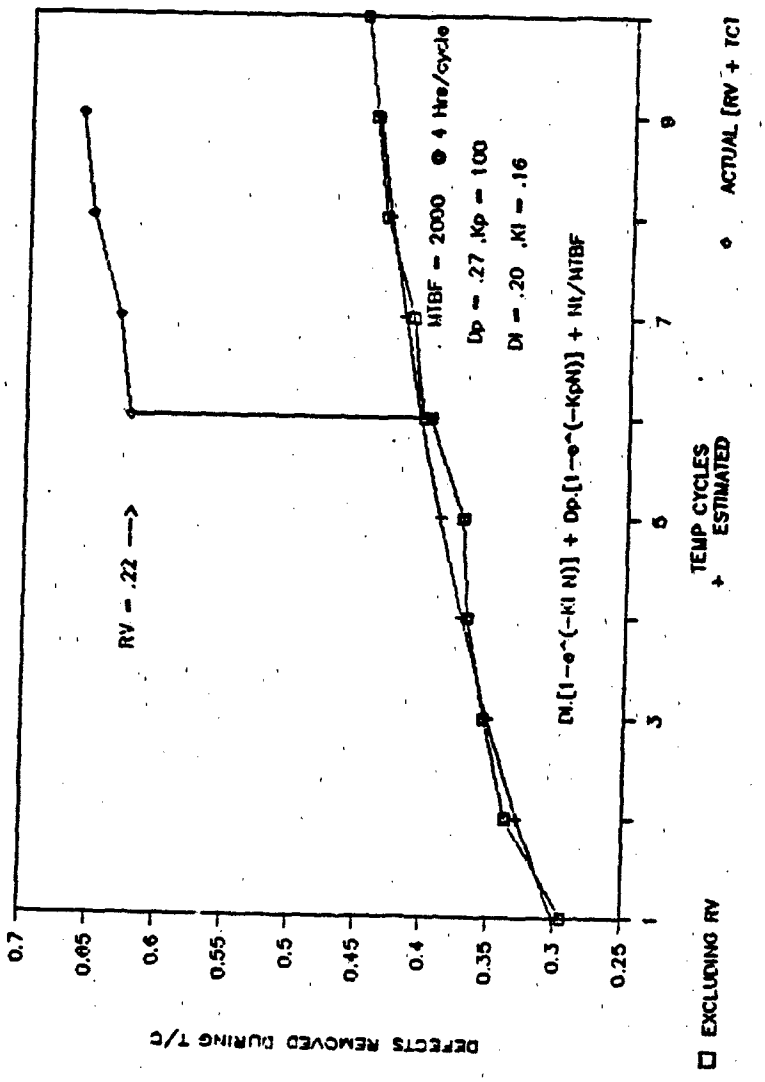


FIGURE 2.21 Equipment C Defect Distribution, 1988.

d) Comparison of Observed and Predicted Screening Strength for all Equipments. The screening strengths (actually precipitation effectiveness) of temperature cycling and random vibration determined above are compared in Tables 2.5 and 2.6 to the HDBK 344 predicted values to examine the accuracy of the HDBK. As illustrated in these tables, the actual results compare favourably with the prediction. The precipitation efficiencies for temperature cycling are compared in Table 2.5. Recall precipitation efficiency = 1-EXP(-Kt)). The average of the precipitation efficiency across all equipments was .20. The average temperature transition range was 119°C.

The comparative HDBK prediction for 120°C, 4°C/min. transition rate was .19 and thus agrees with the observed results.

The precipitation efficiencies for random vibration are compared in Table 2.6. Only Equipment A test flow allowed precipitation efficiency to be measured. The average value of over 2 years was .32 and compared favourably with the HDBK estimate of .35.

The HDBK equations are believed to be useable without modification (other than the change in interpretation and terminology to represent precipitation effectiveness).

TABLE 2.5. Comparison of Actual and DOD-HDBK-344 Predicted Screening Strength for Temperature Cycling.

PROGRAM	YEAR	MEASURED K FACTOR [BI CYCLE^{-1}]	TEMPERATURE PER CYCLES	ΔT [°C]	SCREENING STRENGTH PER CYCLE (1 -e-K)
Equipment A	1987	.17	.75	122	.20
Equipment A	1988	.24	.75	122	.27
Equipment B	1987	.2	1	127	.18@
Equipment B	1988	.25	1	127	.22@
Equipment C	1987	.16	1	110	.15
Equipment C	1988	.16	1	110	.15
				AVERAGE 119	.20
				DOD-HDBK-344	.19
				[ΔT = 120°C, 4°C/MIN]	

TABLE 2.6. Comparison of Actual and DOD-HDBK-344 Predicted Screening Strength for Random Vibration.

PROGRAM	YEAR	K FACTOR [CYCLE^{-1}]	GRMS	SCREENING STRENGTH (5.5 GRMS, 5 MIN
Equipment A	1987	.08	5.5	.33
Equipment A	1988	.075	5.5	.31
			AVERAGE	.32
			DOD-HDBK-344	.35
			[5.5 grms, 5MIN]	

2.5.3 Analysis of Assembly level screening data. Part of the economic optimization process of ESS requires the flexibility of performing ESS at earlier or more cost effective stages of production. It was thus useful to analyze the ESS results from assembly level testing to evaluate the effectiveness of ESS at that stage compared with to system level ESS. The defect and removal data for assembly and system level ESS was provided in Table 2.4. As discussed in 2.4, the assembly data could not be used directly since it contained a mixture of defects,errors,and removal data; thus, the latent defects were estimated using a statistically derived factor. An approximate value for SS was calculated by dividing the assembly level defects by the sum of the assembly and system level defects.

The results of this are shown in Table 2.7 and are of particular concern because of the low value of assembly level ESS. The data indicates that lower level ESS is not as effective as system level. This observation is further supported by the existence of part problems that theoretically should have been eliminated by part rescreening at incoming.
In fact, the data for Equipment A, B and C are similar at assembly level even though Equipment A has parts rescreening and assembly ESS, Equipment B has assembly level ESS, and F-18 has neither (i.e. no lower level ESS).

There are 3 possible reasons for this:

i) defects are not precipitated by assembly level ESS.

ii) the defects are introduced subsequent to the screen.

iii) defects are precipitated but not detected

The possibility that defects are not precipitated is not logically supported by the existence of TC defects at system level and the correlation between actual and predicted precipitation efficiency at system level. To examine the premise that the defects are introduced subsequent to assembly level ESS, the data in Table 2.8 needs to be considered.

TABLE 2.7. ACTUAL SYSTEM AND ASSEMBLY LEVEL DEFECT SUMMARY.

	TOTAL ASSEMBLY LEVEL DEFECTS AND ERRORS ① (DEF/SYS)	ESTIMATED ASSEMBLY LEVEL DEFECTS PER SYS (.25 X TOT)②	TOTAL SYSTEM LEVEL DEFECTS PER SYS	ASSY LEVEL SCREENING STRENGTH③
Equipment A	2.64	.66	1.44	.31
Equipment B, MDI④	5.97	1.49	2.45	.38
Equipment B, MDRI④	4.21	1.05	1.18	.47
Equipment B, HUD④	2.26	.57	1.52	.27
Equipment C	3.59	.90	2.54	.26

① ASSY = CARD AND MODULE LEVEL TESTING
② FACTOR .25 BASED UPON REVIEW OF EQUIPMENT A DATA
③ SS = (DEF AT ASSY)/(DEF AT ASSY + DEF AT SYS)
④ EQUIPMENT B PRODUCTION DOES NOT USE ESS AT THE ASSEMBLY LEVEL

TABLE 2.8. Equipment A System Level Defect Distribution.

FAULT TYPE	TOTAL DEFECTS	TOT ENVIRON-MENTAL DEFECTS	R/V DEFECTS	T/C DEFECTS
TOTAL	1.44	.968	.207	.766
PARTS	.99	.709	.154	.555
WORKMANSHIP	.45	.259	.048	.211

From this table, it can be seen that the TC defect population (.766 at system level) is dominated by part failures (.555) and thus existed (as latent or patent defects) before assembly ESS. The lower assembly level screening strength is thus not explainable by defects being introduced subsequently. The logical conclusion is that defects are precipitated but are not detected until system level testing.

This conclusion is supported by the handbook that suggests that 50% to 80% of precipitated defects require stress concurrent with testing to be detectable. Since assembly ESS is performed without testing during the stress application, the 'observed' screening strength would be between 20% and 50% as limited by detection efficiency.

These results indicate that the effectiveness of assembly level screening strength is dominated by the detection efficiency term and is relatively ineffective because of the absence of a stress concurrent with the test. A stress concurrency factor was thus recommended and included in the revised HDBK recommendations for estimating detection efficiency.

Another interesting observation is that if the thermal shock/cycling associated with the assembly processing eg soldering is considered and modeled then provided SS is detection efficiency dominated the effective assembly level ESS of systems with temperature cycling eg Equipment A and Equipment C is nearly the same as for those with no temperature cycling eg MDI,MDRI,HUD. This would explain the high assembly level fallout on Equipment B as observed in Table 2.8.

The methodology proposed for the handbook addresses these considerations; hence, the ESS optimization considerations and procedures remain valid.

2.6 Analysis of HDBK cost effectiveness procedures. The primary objectives of ESS are to precipitate defects such that their cause can be identified and eliminated (or controlled) and thus defect density reduced and, recognizing that there is a field (MTBF) requirement that is considered satisfactory and thus some level of defect density that can be tolerated, precipitate and remove sufficient defects such that the acceptable defect level would not be exceeded. The ESS program thus i) determines the amount of screening (strength) required to achieve field requirements for a given system complexity and defect density ii) determine the screening type and placement to optimize the factory screening costs and iii) ensure the process is under control.

This approach provides the customer/field with equipment that meets reliability requirements and a methodology for the producer to minimize his production/screening costs and thus customer procurement cost. Since defect reduction improves both reliability and production cost, the optimum tends towards defect prevention. However, it is unlikely that defects can be entirely eliminated; thus, defect removal using ESS remains a requirement to some degree. The cost effectiveness of an ESS program is concerned with the cost of meeting a customer's reliability requirement and must consider both the producer's cost of screening a defect and the cost of a field failure to the user and producer.

The HDBK currently addresses the combined user producer cost by assuming the cost of a defect in the field to be $1000. This value then becomes a "threshold" cost and has the implication that if the cost of factory ESS exceeds $1000 per defect, it may be more economical to reduce factory ESS and let the defects occur in the field for non-critical systems. However, for mission critical high reliability systems, cost would be of secondary concern.

Consistent with this intent, the HDBK procedures were modified such that if reliability requirements can not be achieved the ESS plan would be required to provide the projected marginal cost per defect i.e. the factory ESS cost of removing the excess defect per system. The procuring activity could then determine whether this value is reasonable compared to the cost of a defect in the field and whether reliability requirements could be relaxed for certain cost considerations. The $1000 threshold provided in the HDBK is a reference guide only and must established by the customer. In the absence of a known threshold cost, the optimization procedures should assume that the desired reliability must be achieved and thus provide the user with the methodology for designing or modifying the screening program to minimize screening cost and/or to optimize the cost of achieving the required field MTBF. Although the amount of screening required by the producer is determined by the field reliability requirement and defect density-complexity of the equipment, the producer has flexibility in what screen to use, the stress level, and the position of the screen in the test flow and has constraints on the assembly-test sequence due to calibration and performance verification testing and constraints on permissible stress levels imposed by the equipment design. The cost analysis procedure assists the producer's optimization of these trade offs.

The methodology of Procedure D identifies fixed costs which are actually the non recurring costs to establish the screening capability (for a given program) and variable costs, which are the recurring costs for performing the screens.

The principle factors considered in the cost analysis and identified in Procedure D are:

i) cost of testing
ii) cost of environmental stressing
iii) cost of repair/rework and associated analyses
iv) cost of repeating stresses and tests, depending upon the test flow/failure free requirements

It should be noted that the HDBK approach optimizes the cost based on the program cost by combining the non recurring cost with the recurring cost per system multiplied by the total systems to be produced. An alternate approach is to amortize the non recurring costs based upon ESS equipment useful life and utilization, thereby converting all costs to a per system bases. This later approach is useful when the equipment can be shared among several programs and/or if the programs have an indeterminate total quantity.

The cost optimization methodology was applied and validated by the study, however, cost results are company confidential and thus not provided in the report. The methodology however is illustrated in 5.0.

2.7 Analysis of HDBK Failure Free Acceptance Testing (FFAT). The present HDBK contains a requirement for a Failure Free Acceptance Test (FFAT) as described in HDBK para. 5.4, Procedure C. The mathematical derivation is provided in Appendix C of the HDBK.

The validation and analysis performed on the HDBK's FFAT concerned i) the validation of the mathematical model and procedure, ii) validation of the assumptions used for the model and iii) a review of the implications of FFAT in general. A computer program was specifically developed to analyze the FFAT mathematics and procedures.

The FFAT derivation given in Appendix C of the HDBK was reviewed and validated with the exception of a typographical error in equation C-4 (i.e., should be $\exp[-D \exp -(\lambda_D t)]$ and concerns related to the model assumptions that are discussed below.

As an illustration, the $\lambda_D t$ - λ_D/λ_0 tables in the handbook (ref. Tables 5.19 - 5.20) were recreated using the developed software and Figure 2.22 herein can be seen to correlate with HDBK Table 5.19 and thus validates the handbook mathematics.

90% Lower Confidence Bound on Yield

Ld/Lo	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.2	0.255	0.003	0.001	0.000	0.000	0.000	0.000	0.000	0.000
0.3	^	0.101	0.024	0.012	0.008	0.006	0.005	0.004	0.004
0.4	<	0.541	0.139	0.071	0.047	0.036	0.030	0.026	0.023
0.5	<	^	0.375	0.197	0.134	0.104	0.086	0.075	0.068
0.6	<	<	0.692	0.377	0.262	0.205	0.172	0.151	0.137
0.7	<	<	^	0.580	0.411	0.326	0.277	0.245	0.222
0.8	<	<	<	0.781	0.564	0.453	0.388	0.345	0.316
0.9	<	<	<	0.965	0.709	0.577	0.498	0.446	0.410
1	<	<	<	^	0.839	0.691	0.601	0.542	0.500
1.1	<	<	<	<	0.950	0.791	0.694	0.630	0.583
1.2	<	<	<	<	^	0.878	0.776	0.703	0.659
1.3	<	<	<	<	<	0.950	0.846	0.776	0.725
1.4	<	<	<	<	<	^	0.906	0.835	0.783
1.5	<	<	<	<	<	<	0.955	0.884	0.833
1.6	<	<	<	<	<	<	0.996	0.926	0.876
1.7	<	<	<	<	<	<	^	0.961	0.912
1.8	<	<	<	<	<	<	<	0.990	0.942
1.9	<	<	<	<	<	<	<	^	0.967

Ld =

Note lambda is represented by the letter L in the above tables

FIGURE 2.22. Validation of DOD-HDBK-344 Table 5.19.

Although the mathematics described by HDBK Appendix C were applied to an FFAT, problems were uncovered with the details of Procedure C of the HDBK. Following from Appendix C, the FFAT is determined based upon the amount of 'testing' required to ensure that the MTBF at the completion of testing meets system requirements with some specified confidence level.

The specified parameters are thus i) the required system λ_S ii) the desired confidence level, and iii) the inherent λ_0.

The user has only one degree of freedom and can thus select only one of λ_D (failure rate for defect), D_{IN3} (initial defects at start of FFAT) , or T (duration of FFAT). Having selected one of these parameters, the other two are determined by solving the equations in Appendix C. If the user selects a λ_D (i.e. this is equivalent to specifying a screening stress level), then the HDBK Tables 5.19 - 5.28 can be used to solve for T and hence D_{IN3}. These calculations and procedures are performed by the LSL software.

This is illustrated in Figure 2.23 where the analysis software was used to determine the FFAT for a system with a required λ_S of .001, an inherent λ_0 of .000909, a confidence level of 90%, and a selected λ_D of .01. For this example, D_{IN} MAX was found to be 1.82 and would give a first pass factory yield of 10% (i.e., confirming the 90% confidence limit).

```
Specify
        System failure rate          0.0010          thus MTBF=     1000
        Lo failure rate              0.0009          thus MTBF=     1100

        Confidence level for FFAT                90%
Calculate
        The system failure rate due to defects is thus:

         Ld.DEFout =                 0.0001          MTBF          11000
Select
        Stress level / Ld =            0.01         MTBF            100

Calculate
         DEF out=                   0.0091

        Yield (=exp(-DEFout))        99.10%  {percent defect free systems
                                              in field after ESS & FFAT}

        Ld/Lo=                          11

Determine
        Ld.T =                          5.3   {use tables or iterative solution

Calculate
        TEST HRS=                       530
        Starting def =              1.8212

        FFAT Screening Strength      0.995

        Probability of passing failure free=          10.09%
          ie should = (1- specified conf.)

        First pass "FFAT" yield vs defects/system:

                    DEF       1st pass yld
                      0          61.77%
                  0.001          61.70%
                   0.01          61.15%
                    0.1          55.92%
                   0.25          48.16%
                    0.5          37.56%
                   0.75          29.29%
                      1          22.84%
                   1.25          17.81%
                    1.5          13.89%
                   1.75          10.83%
                      2           8.44%
                    2.5           5.13%
                      3           3.12%
```

FIGURE 2.23. Failure-Free Acceptance Test 'FFAT' Example

Note lambda is represented by the letter L in the above tables.

The problem associated with the procedural details is that steps 2, 5, and 7 imply that there is more than one degree of freedom and that the user can arbitrarily select or determine D_{IN3}, TS and SS. This is not believed to be possible and thus Procedure C would need to be rewritten. Before considering rewriting Procedure C, however, the assumptions and rationale of an FFAT need to be re-examined.

The derivation of the FFAT is based upon Appendix C equation C-2.

$$1 - CONF = \exp [-\lambda_0 T - D (1 - \exp (-\lambda_D T)]$$

The problem with applying this equation is that λ_0 and λ_D relate to different stress levels. If the user selects a higher factory stress level, for example, a λ_D for 5 g RMS vibration as opposed to 1 g RMS, then λ_0 should also increase since both are a function of stress level (s). The λ_D term inherently addresses the relationship with stress; however, the stress dependency is missing for λ_0.

In this sense, the equation is an "apples and oranges" mix; hence, its solution is not necessarily valid. When applying the FFAT procedure the user can not arbitrarily select λ_D without affecting λ_0 and the Procedure is thus believed to be flawed.

From the foregoing, the FFAT seems to be flawed from theoretical and procedural aspects. From a philosophical aspect it is also undesirable.

The concept of an FFAT is contrary to the purpose of ESS and the HDBK in that the FFAT determines the minimum ESS program and prevents the user from optimizing or reducing the screening program to be less than the FFAT minimum. This can remove the incentive for the user to reduce defects since the possibility of a defect density - screening strength trade off is eliminated by the imposed minimum screening requirement of the FFAT.

These points are illustrated in the example provided in Figure 2.22. For the desired 90% confidence FFAT, the $\lambda_0 T$ is required to be 5.3 (i.e., 530 hrs screening at $\lambda_D = .01$), the required screening strength [i.e., 1 - exp ($-\lambda_0 T$)] is thus 0.995 regardless of the initial defect density. If the user were to reduce the defect density to 0 through effective corrective action, the FFAT would be unchanged and, even with zero latent defects, the producer would suffer a

FFAT yield of 62% (due to the limiting failure rate λ_0). In this example, a zero (screenable) defect system would still require 530 hrs. at a yield of 62% Resubjecting the "failed" system to the FFAT would incur a subsequent 62% yield and the user would becomes caught on a costly vicious circle and the average screening time per system would approach 680 hours. The extended screening time would shorten the useful life of the equipment and could be sufficient to induce fatigue type failures soon after shipment and would also adversely affect the cost of the equipment due to the unnecessary test and rework costs (for λ_0 failures).

The FFAT is structured such that if the producer achieves the required λ_S, then his first pass FFAT yield is 1- CONFIDENCE, i.e., 10% for a 90% confidence FFAT and he is thus severely punished for meeting requirements. Because of the low discrimination ratio for an 'accept on zero' type plan, the FFAT confidence levels need to be carefully considered and set and may need to be less than 90%.

Since a lower confidence level may be viewed as unsatisfactory by the customer, an alternative means of demonstrating reliability other than FFAT is required. The recommended approach is to use SPC and the available data from the HDBK 344 ESS Program. In essence, the purpose of the FFAT is to provide confidence that the systems are sufficiently defect free. This confidence however can be obtained from the SPC of the ESS fallout without the cost of redundant and perhaps unnecessary testing.

The preferred approach for of ESS would be that, provided sufficient corrective action can not be taken to prevent defects, all systems undergo similar screening that has a sufficient strength to ensure that field reliability requirements can be achieved. The emphasis is thus on defect prevention with ESS being a "short term" solution. During ESS, it is useful to expose all systems to the same amount of screening in order to have a more controlled fatigue life distribution thus permitting regularly scheduled, preventive maintenance to be used to maximize the gains in MTBF afforded through defect prevention and ESS.

2.8 Analysis of HDBK Statistical Process Control Methodology. If the ESS program is to be controlled and used to indicate compliance with reliability requirements, some form of monitoring is required. The HDBK recommends

the use of Statistical Process Control (SPC) and PARETO charts for this purpose. This methodology and recommended changes are discussed in the following.

a) DOD-HDBK-344 Procedure E requires SPC charts to be prepared for these ESS parameters:

i) INCOMING DEFECTS

ii) FALL OUT

iii) OUTGOING DEFECT DENSITY TO OUTGOING DEFECTS

These charts are based on a Poisson distribution, i.e., mean = variance = μ and belong to a class of SPC chart that is based on attributes (i.e., C chart) rather than variables (X and R charts). [Ref. STATISTICAL QUALITY CONTROL, E.L. GRANT, and R.S. LEAVENWORTH, MCGRAW HILL].

The methodology described in the handbook suggests SPC monitoring on an individual system basis. For ESS monitoring, however, it would be preferable to use a normalized monitoring scheme based on the average defects per system ie defect density.This type of monitoring chart is a "U" chart where u = total nonconformities/total units inspected. The control limits are based on $u \pm 3\sqrt{(u/n)}$ where n is the sample size.
In addition to being more directly related to ESS parameters it permits the user to also track performance on a time basis, eg., daily/weekly/monthly, etc. and since n can be made large, the sensitivity can be increased (i.e., Sigma $\rightarrow$ 0).

These charts in essence monitor the variation in the mean defect density and are thus a test for homogeneity. The inherent problem is that TQM and ESS approaches are aimed at continuous improvement; thus, the process mean should be continually improving and not remain constant.

A suggested modification to the HDBK and SPC approach is to determine the current process capability using regression analysis and thus attempt to detect and quantify the improvement rate. The expected variation due to limited sample size would be determined using this value for the process capability

(mean) and the expressions given below. This variation would be plotted as control limits (using the formula given above) and used to identify possible short term trends and problems.

When applying these charts for small sample sizes, the quantization effect can become significant and may create the misconception of an out of control process. For example control limits of u ± .01 can not be resolved with a sample size of 10 since the actual data could only be plotted with a resolution of ±.1.

Since the purpose of the ESS is to ensure that customer reliability requirements are satisfied, the control chart must reflect the requirements as well as the current process capability. It is not adequate to merely 'control' the process. The process must both be in control and capable of achieving requirements. (Aside: The definition of requirements may also require further clarification. Presently most requirements relate to a mean of some performance index, eg., MTBF, DPM, etc., however there may be a need to also specify the allowable deviation, eg., more than X% of the systems must have less than Y defects.)

To resolve these concerns and simplify the application, LSL has developed PC software to produce a modified form of SPC control chart. The software accommodates a variable sample/production size and adjusts the 'control' (actually statistically expected variations) limits accordingly. The requirements are determined directly from the ESS program plan and therefore are directly related to required field reliability. An illustrative example of the modified SPC chart is shown in Figure 2.24.

b) PARETO Charts. A useful chart to help identify the cause of problems is the PARETO chart. The PARETO typically examines the frequency of various causes of non conformities. A concern with the PARETO, however, is that a conventional PARETO identifies the most frequent cause but not necessarily the most important cause and can over look what is expected based upon other considerations, for example complexity.

To overcome this, a modified PARETO is suggested that charts not only actual results, but compares them with the expected results based on complexity and statistical significance.

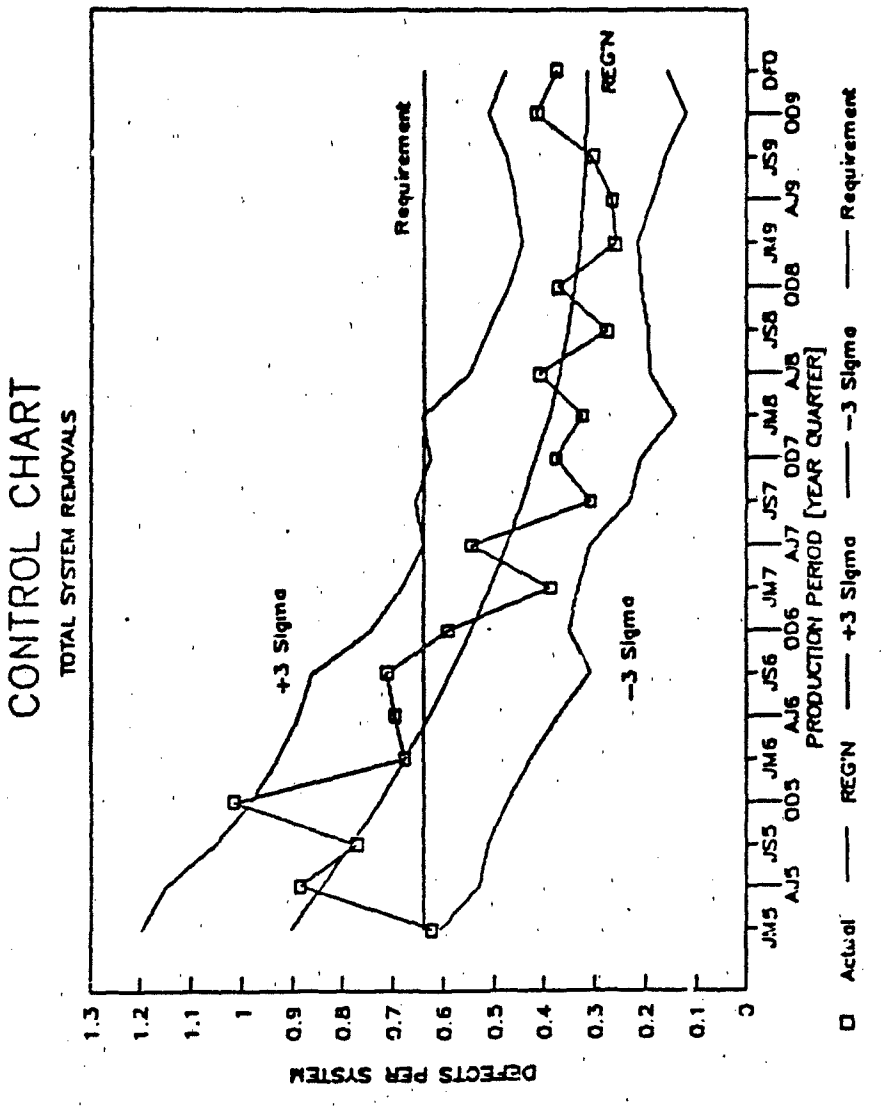


FIGURE 2.24. Modified SPC Chart.

A PARETO analysis software package was developed by LSL for this purpose and would be used on a routine basis to compare actual to expected defects/system for the various assemblies and subassemblies.

An illustrative example of the modified PARETO is provided in Figure 2.25. This modified PARETO compares the actual defects per assembly to the values that were expected based on assembly complexity and determined during the ESS planning phase. To allow for statistical variation due to sample size, the expected values are indicated as ±3 sigma bars (assuming a Poisson distribution). More conventional PARETOs can be produced if desired.

The SPC charts on Total Defects, Part Defects and Workmanship Defects, etc., are useful to indicate the overall status; however, the PARETO for assemblies is useful to identify possible design weakness or faults. Since a design fault is often specific to a particular assembly, the PARETO identifies those assemblies with defect densities above expected levels (based on the overall process capability for parts and workmanship), and thereby identifies possible design weaknesses for more indepth analysis.

Conversely, assemblies with abnormally low defects may indicate test detection efficiency problems, or low screening stresses. As discussed in the current HDBK, the user must be vigilant and examine all abnormal results for both 'good' and 'bad' indicators.

c) Relating Required Reliability to Remaining Defects. The monitoring and control procedure described in the HDBK if modified as suggested herein can be applied and used for an effective control program provided the customer reliability requirements can be related to ESS parameters, eg. Outgoing Defect Density.

A consistent methodology for establishing this relationship however, does not presently exist in the handbook. A related problem is that the method for determining what screening strength is required based upon the plan and/or the actual observed defect densities also does not exist.

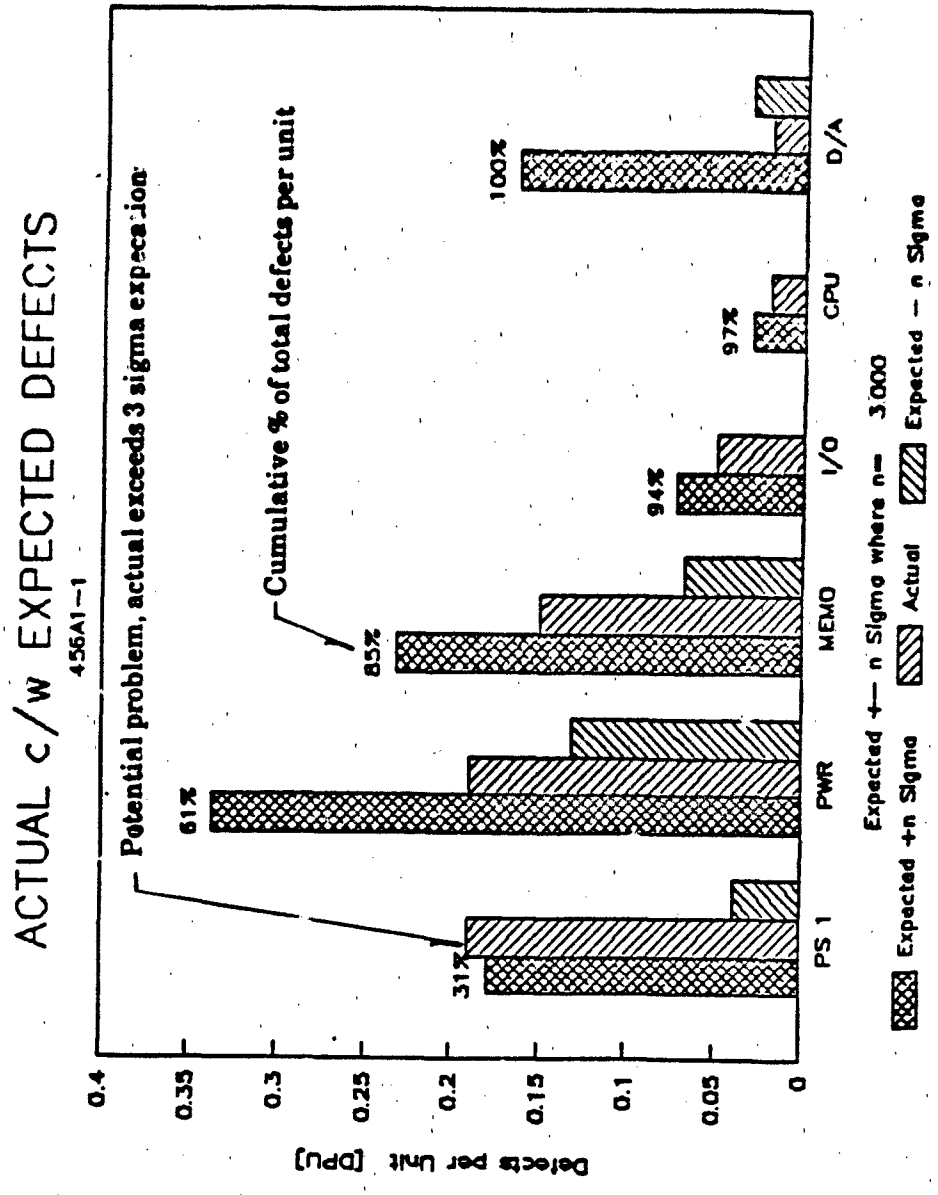


FIGURE 2.25. Modified PARETO Chart.

The procedure should be able to determine the screening strength required to satisfy customer reliability requirements assuming the HDBK estimated defect densities are being achieved. If however, the requirements established in the plan are not being achieved, the user also needs a methodology for determining how much additional screening strength is required, until the process is back in control and/or in line with the plan.

There are two methods available to the user for translating reliability requirements into a factory requirement for remaining defects (per system). The first method is to model the field operating environment in terms of actual stress levels and conditions eg temperature cycles with temperature range and transition rate and vibration with G level (power spectral density) and duration. Knowing these conditions, the user can then directly apply the precipitation efficiency equations given in the HDBK. Since the detection efficiency of the field is 1 (by definition) the screening strength is equal to the precipitation efficiency and is thus known for the corresponding duration in the field. The defects occurring over this field operating interval are then determined as the product of the remaining defects (at the conclusion of factory ESS) times the screening strength of the field.

The maximum allowable defects remaining at the completion of factory ESS can thus be expressed in terms of the maximum allowable field defects as follows:

Maximum Defects (field stress) = Maximum allowable field defects / Field Screening Strength.

The maximum allowable field defects can be determined by multiplying the required MTBF by the operating interval. This expression determines factory defects relative to the operational stress levels. To determine the defects relative to the factory ESS stress level, this value would be multiplied by the appropriate stress adjustment factor.

The second method would be used if the actual field stress conditions are not known or available and uses equation 2.2 with an appropriate value for K. The (1-e-kt) term in this equation is the precipitation effectiveness of the field and thus determines the screening strength as discussed above. The remaining calculations would be performed as described for method 1 above. The value of K can be determined from experience data and or published literature and is probably in the order of 1/300 to 1/1000 hours depending on operating environment.

In summary, a field requirement fo. MTBF or FFOP can be translated into a factory requirement for the maximum outgoing defects per system. This is accomplished by using either of the methods outlined above to estimate the equivalent screening strength of a specified interval in the field. This estimate of field screening strength should be refined as actual data becomes available.

PART C

1. Introduction. The study program required the ESS methodology of DOD-HDBK-344 to be applied under actual factory conditions and the results used to determine and correct deficiencies in the procedures. Part B described the application of the HDBK, the analysis of the observed results, and various recommendations for changing the handbook. This part provides a procedure by Procedure critique of the HDBK and describes specific problems and the recommended changes. Part C thereby relates test the results of Part B back to the HDBK and explains the reasons for revised handbook prov.ded as Part D.

2. Procedure A1 Incoming Defect Density Requirement.

a) Purpose. To provide assurance that the part fraction defective is below R&M 2000 policy guideline, i.e., 100 DPM (FY90)

b) Comments.

i) A current industry interpretation is that the 100 DPM requirement is applicable to electrical test, i.e., patent errors. It is important to recognize that latent defects determine reliability and should be the concern of HDBK 344. The Electronic industry must address latent defects as well as patent errors.

ii) The significance of the 100 DPM level needs to be determined based upon specific reliability requirements. The proposed HDBK provides the methodology for determining the appropriate level, whether it be greater or less than 100 DPM. Referencing the 100 DPM guideline in the HDBK is thus unnecessary and potentially misleading.

iii) EIA Procedure 554-88, may be useful for measuring outgoing non conforming levels in DPM.

3. Procedure A2. Estimating Incoming Defect Density. The recommendation is to eliminate the direct reference to the 100 DPM guideline.

a) Purpose. To estimate the incoming defect density (Din)

b) Comments.

i) The procedure estimates factory incoming defect levels based on the operating environment. This approach is not applicable when estimating factory ESS fallout since factory stress levels do not directly relate to the operational environment. The recommendation is to create a defect density data base that is applicable to a reference or base line stress level equivalent to R&M 2000. Applicable defect densities at other stress levels would be obtained using an appropriate Stress Adjustment Factor /SAF.

ii) The procedure assumes Din increases with stress, i.e., is a function of the operating environment. Since factory ESS stress levels must be higher than the application, the implication is that defects screened may be relevant or non relevant. The basic HDBK model is thus not adequate and stress effects must be included.

iii) Din is expected to vary with time and product maturity (ref HDBK 4.10.3.3.2 and the study results). The direct application of HDBK tables thus has questionable accuracy, and the user must be provided with a methodology to rescale the tables based on experience.

iv) the level of accuracy that is required must be kept in perspective. The tables of defect density should be used for initial planning purposes only (ref. HDBK 4.10.2.3.1)

a) Defect densities for parts and workmanship (hence goals and ESS) must be adjusted based on users actual data,

b) the procedure should outline the method of estimating Din and SS, etc. from factory fallout data

c) the procedure should emphasize maximum use of user data

v) The perception of defects being either part or workmanship may be affected by the degree of root cause analysis and the classification guidelines. Without detailed analyses, many of the problems due to design or workmanship may be incorrectly perceived as part problems. The comparison of defect density data among different users must thus be made with caution. It is noteworthy that the LSL results did correlate with the HDBK guidelines ref. 4.10.2.3.3 on the fraction of parts and workmanship defects (after the LSL recommended changes, e.g., using MIL-STD-2000 for complexity).

	Parts	Workmanship
LSL	67% - 83%	17% - 33%
HDBK 344 (ref. 4.10.2.3.3)	60% - 70%	20% - 30%

vi) The HDBK acknowledges the need to proportion Din as RV and T/C defects (ref. HDBK 5.2.3.1). This is necessary to achieve the correct balance of RV and T/C screens. The LSL results indicate that RV and T/C defects tend to belong to different populations and thus it may be unrealistic to expect T/C to remove RV defects and vice versa. The detailed procedures in the HDBK need to be changed to emphasize the need to proportion defects into RV and TC defect populations.

The LSL results correlated with HDBK results concerning the proportion of RV and T/C defects.

	RV	T/C
LSL	26%	74%
HDBK 344	20%	80%

3.1 Procedure B. Determining Screening Strength.

a) Purpose. To determine the 'Test Strength' TS = SS.DE (Note with the recommended changes in terminology this becomes SS = PE x DE where SS is screening strength, where PE is Precipitation Efficiency and DE is Detection Efficiency.)

b) Comments.

i) The significance of testing concurrently with stress application should be emphasized. For example, if the assembly level test coverage is 85 - 99% (ref. HDBK table 4.6) and 50 - 80% of defects require stress for detectability (ref. HDBK 4.10.3.4.2) then the assembly level SS is low (.17 - .5). This low value of TS (i.e. now SS) was observed by the study during assembly level screening (i.e., <.3).

iii) The limited DE implies that undetected patent (precipitated latent) defects will escape to the next stage. This can create an apparent 'on receipt' or 'infant mortality' problem. The analysis procedures must thus recognize escaping patent defects.

iii) The estimate for RV precipitation effectiveness must be modified to recognize an axis sensitivity (ref. HDBK 4.10.3.3.3.C). The study revealed a strong axis sensitivity factor i.e. perpendicular to the plane of the PCB's. The complexity vectors should be computed for the x, y, and z axes and the calculation of PE for RV adjusted in proportion.

iv) It is important to emphasize that the stress parameters (t, dT/dt, grms, etc.) should apply to the unit under test (UUT) not the

chamber. The calculation and modelling must thus include stress transmission characteristics (ref. HDBK 4.10.3.5) and recognize that g levels may be enhanced or suppressed and dT/dt is limited by thermal mass and conductivity.

Further, stress levels vary over the equipment/assembly complicating identification of the appropriate stress parameters and thus application of the tables. Thermal and vibrational surveys on the simulated or completed hardware may be required.

v) The study validated the PE tables for RV and T/C (for the particular stress levels used). However, the stress levels cited (especially for RV) may need to be rescaled to be consistent with iv. The stress levels used for the tables should be the actual stress levels to which the equipment is subjected. Because of equipment transmissibility, these values are different than the stresses measured at the output of the ESS chambers and shakers. Because the HDBK tables and equations were derived using data from actual equipment, the stress levels given in the tables imply ESS output levels but actually represent the levels seen by the equipment under test . These levels should be multiplied by the transmissibility of the equipment used for the data collection in order to make the tables more generic.

vi) The HDBK mathematical model can result in significant errors if incorrectly applied. Using the current HDBK terminology, the model is based on $TS = SS \cdot DE$. Thus, TS_{cum} is given by $1 - \pi_i (1 - TS_i)$ (ref. 40.7 eq. A-10) the resulting TS_{cum} is thus asymptotic to 1. However, although the SS_{cum} is asymptotic to 1, TS_{cum} must be asymptotic to the detection efficiency (DE). Provided similar tests are not repeated, the error is probably not significant; however, successive tests of a similar nature could result in significant modelling errors.

3.4 Procedure C - Failure Free Acceptance Test

a) Purpose. To provide a level of assurance that screening is (sufficiently) complete (ref. HDBK 4.10.3.8)

b Comments.

i) The procedure uses extended testing at high stress to provide a statistical confidence level on the remaining defects. The procedure has no consideration of prior ESS results and requires a fixed, demonstration ESS be performed (or repeated) regardless of defect levels and SPC performance. For this reason FFAT is not considered to be economically prudent.

ii) The mathematical basis for the FFAT (Appendix C equation C-2) involves mixed stress levels) i.e. λ_0 is at the operating stress and λ_d at ESS stress and the accuracy is thus questionable.

iii) The procedure cannot be used as written since the user has only 1 degree of freedom in selecting stress levels or duration and would need to be modified.

iv) Imposing an FFAT can impact and penalize the user for achieving the required reliability.

If its user satisfies the required reliability, the first pass yield would be 1 minus the confidence level, eg., if the confidence level is 90% the factory yield would be 10% and the producer would be required to rework 90% of 'good' systems. The low yield would be caused by failures due to the design limit occurring at a constant failure rate (CF) and thus, could not be improved without redesign. Extended test times are required, even if D_{latent} is zero. The unnecessary testing and rework increase cost and potentially degrade reliability.

v) The FFAT may dominate over the HDBK 344 Quantitative/Adaptive approach - i.e.,the minimum ESS testing imposed by FFAT can exceed the ESS required to achieve goals, thus the FFAT is self defeating for HDBK 344.

vi) The recommendation is to use SPC techniques and the results of the entire ESS to demonstrate that defects remaining are 'acceptable'.The FFAT would be used to represent some minimum

level of ESS that would need to be retained, even if results indicated that ESS could be eliminated in its entirety. Although the goal of ESS is to eventually make ESS unnecessary (i.e. defect causes are identified and eliminated and latent defects driven to extinction) a certain amount of stress testing is required to demonstrate the process is in control.

3.5 Procedure D - Cost effectiveness analysis.

a) Purpose. To optimize the cost of the ESS program

b) Comments.

i) The procedure analyses the cost of various screening options (screen type selection and placement) to identify the most cost effective plan. The concern with the HDBK procedure is philosophical in that the HDBK uses a cost threshold of $1000/defect to represents field repair cost and could have the mistaken implication that if user's ESS cost/defect can not be reduced below $1000/defect, then the defect level is adequate (4.10.3.7). Also, the threshold cost can be expected to vary with time and equipment, eg., the HDBK also cites 10-15k$/defect (ref. HDBK para. 4.4).

ii) The HDBK procedure should be changed to emphasize and include the following:

- reliability requirements must be achieved
- the user optimizes the cost using HDBK 344 to
    i) prevent defects
    ii) screen what is not preventable
- SPC techniques are employed by the user to
    i) demonstrate that requirements are being achieved
    ii) strive for quantitative, continuous improvement beyond compliance based on economic trade offs

The ESS plan should predict the 'marginal' cost of defect elimination (i.e. the cost of screening the last factory defect) so that if the specified reliability can not be economically achieved, the customer and producer can assess the economic tradeoffs of relaxing reliability requirements for cost considerations.

The HDBK procedure performs the cost analysis on a program life basis (i.e., total systems to be produced). The recommendation is to change this to a per system basis.

3.6 Procedure E - Monitoring, Evaluation, and Control.

a) Purpose. To monitor, evaluate and control ESS and manufacturing to assure that the requirements for remaining defects are achieved

b) Comments

i) Monitoring evaluation and control using SPC techniques are fundamentally necessary for an effective ESS Program.

The problems that need to be addressed are

a) what parameters should be monitored

b) how can these parameters be measured and

c) how do they relate to customer reliability or cost requirements.

ii) The purposes of monitoring and control are

a) to ensure the outgoing product meets reliability requirements

b) to ensure in-house TQM goals are being met and

c) identify the cause and corrective action for out of control conditions.

iii) The key elements of management monitoring are thus a set of performance indices and established goals (and warning limits) for these indices and a means of comparing actual performance with these requirements. The critical parameters for monitoring and control are thus $D_{remaining}$, screening strength, Defect Density, Defects Removed, and Cost. Since only observable statistics are fallout (ref.HDBK para. 4.11.4 i.e. DR (defects removed)) procedures must be provided to determine values for the parameters of interest from the factory fallout.

3.7 Procedure E1.

a) Purpose. To estimate Din and SS (procedure A and B) to make inferences regarding remaining defects.

b) Comments. From foregoing discussions and the HDBK (ref. 4.11.4.3) the actual and predicted values of Din and SS can differ significantly. Since neither Din nor SS can be evaluated using procedure E1, the procedure has limited and questionable use and procedure E2/E3 is preferred.

3.8 Procedure E2/E3.

a) Purpose. To estimate Din, SS, and ($D_{remaining}$) using a curve fitting methodology.

b) Comments.

i) In principle this technique is similar to that used in the study contract. To be practical though, the user needs software tools to assist in the curve fitting analysis. The tools must be flexible since several options and criteria are possible for curve fitting and there is not one unique or 'best' solution. For the study contract, LSL developed PC software to assist in the curve fitting analysis.

ii) Because there is no single solution with the curvefitting methodology, analyses made by the same user are reasonably self consistent; however, comparison of analyses made by different users requires caution.

iii) The mathematical model for curve fitting must include a patent defect term and constant failure rate and may be required to model time dependent detection, thus, the Chance Defective Exponential (CDE) model needs enhancement.

3.9 Procedure E SPC Charts.

a) Purpose. To demonstrate that the process is under control (i.e. reliability is being achieved) or conversely identify when the process is not in control and additional ESS and/or special action is required.

b) Comments.

i) The HDBK SPC charts are based on the nonconformances for individual systems. A recommended change is to track the normalized statistic eg. defects per unit (DPM or DPU) calculated from the average defects per system in a batch of N systems since these parameters are more directly related to ESS parameters and can track performance with selectable sensitivity.

ii) Conventional SPC charts are often a test of homogeneity. For ESS purposes, defect densities are expected to improve (through corrective actions to eliminate defect causes); thus, it is appropriate to track the moving process capability and use statistical significance tests to determine if the process is out of control. The recommended SPC chart was described in Part B.

iii) It is not adequate to merely demonstrate control. The process must be capable of achieving the required field reliability. The reliability requirements must thus be translated into a corresponding factory requirement and included on the SPC chart.

iv) A Failure Free Acceptance Test (FFAT) is proposed in the HDBK as a means of 'ensuring' that the remaining defects are below the required level without actually estimating their magnitude. The FFAT is undesirable from an ESS and producer's aspect; however, if FFAT is not used, an acceptable viable alternative to FFAT is required.

The SPC control techniques can be directly used for this purpose. The use of the curve fitting software/methodology not only determines the D_{PAT}, D_{LAT}, SS, etc. but also inherently estimates the remaining defects. The remaining defects can be charted on similar SPC control charts to those discussed above and thus used to indicate compliance with requirements. The requirement for $D_{remaining}$ would be established using the method described previously.

The SPC approach is recommended over the FFAT since it is consistent with TQM, and allows the user to reduce incoming defect density (D_{iN}) as an alternative to screening and to tailor the factory ESS program based upon measured D_{iN} and the field reliability requirements.

4. PROPOSED CHANGES TO THE HDBK

This section provides a summary of the purposes changes to the handbook.

4.1 The proposed changes to the handbook are illustrated in the revised model shown in Fig 4.1. The proposed changes do not affect the basic concepts and methodology described in the HDBK and the incoming defects per system are calculated in a manner similar to the current handbook. The complexity of the system is described by the number of items in various type-reliability grade categories. The defects per system are then calculated by multiplying each of these complexity values by the corresponding defect density for each category. The recommended changes however modify and affect the estimate of incoming defects as follows:

i) Workmanship complexity and thus defects are determined based upon the MIL-STD-2000 assembly and solder complexity numbers. This change was made to improve the accuracy of the estimated workmanship defects.

ii) The defect population (ie parts and workmanship) is proportioned into separate populations that are sensitive to RV and TC stresses. ESS calculations are subsequently performed on these separate populations. This change was made to improve modelling accuracy and to ensure a proper balance of RV and TC screens.

iii) The defects are determined relative to the R&M 2000 stress levels. These stress levels are defined to be the reference or baseline stress levels. Defect densities for other factory ESS stress levels are determined by multiplying the reference values by an appropriate Stress Adjustment Factor (SAF). The values of field defects under different operating environments calculated using the defect densities for that environment, eg. AIF, etc.

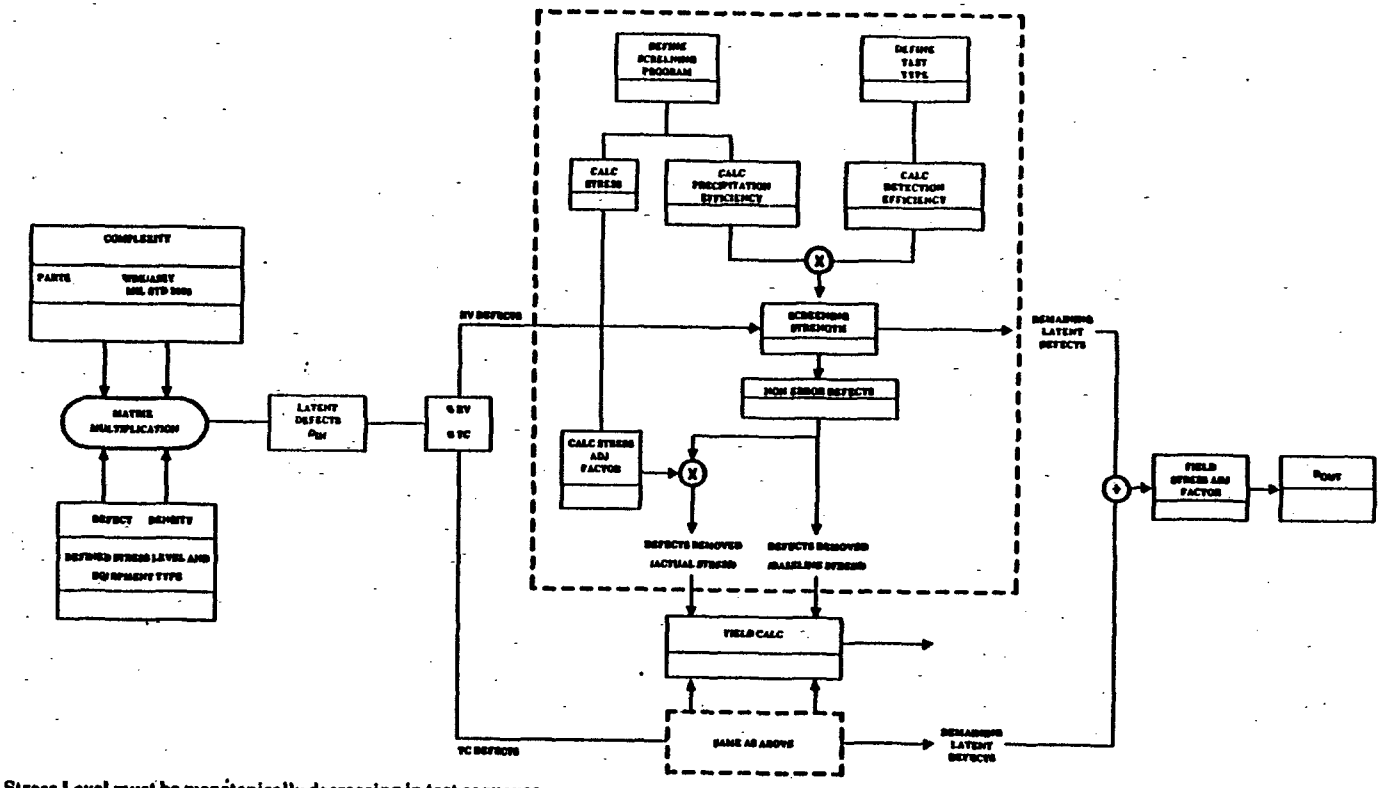


FIGURE 4.1. Revised ESS Model.

NOTE: 1. Stress Level must be monotonically decreasing in test sequence.
2. Undetected precipitated latent defects included in latent defects for simplification.

the mathematical model can be represented by:

$$DREMOVED = DE \times DPAT + DE \times DLAT[1 - \exp(-kt)] + DE \times CFR \times t \quad (A\text{-}9)$$

where DE = detection efficiency
DPAT = patent defects
DLAT = latent defects
k = stress constant
t = stress duration
CFR = constant failure rate

4.2 The calculations of defects removed and defects remaining are also similar to the existing handbook in that the defects removed are calculated by multiplying the system (or assembly) defect density by the applicable screening strength. The recommended changes affect the procedures as follows:

i) the defects removed by screening are calculated relative to the baseline stress. The actual defects removed are then calculated by multiplying the removals by an appropriate stress adjustment factor.

ii) the terminology was changed from test strength = screening strength x detection efficiency to screening strength = precipitation efficiency x detection efficiency. This change was made to make the terminology more consistent and descriptive.

iii) precipitation efficiency is determined using the same equations as those used to produce to present HDBK tables. The precipitation efficiency for RV however was modified to include an axis sensitivity factor. This change was made to improve modelling accuracy based on the axis sensitivity observed in the study.

iv) the stress parameters eg Grms, Temperature transition rate etc are defined relative to the unit under test and not the environmental chambers etc. The requirement for thermal and vibrational surveys to determine appropriate values was also added. (Consistent with this change, the stress level in the precipitation efficiency equation may need to be rescaled.)

v) the requirement to calculate the damage factors due to the ESS was added to ensure that the ESS stress levels and duration are not destructive or consume a significant portion of the useful fatigue life.

4.3 Further changes and refinements concerned the data analysis and SPC procedures and the requirement for FFAT.

i) The procedures were modified to encourage the maximum use of observed data. Initial estimates of defect density and screening strength are made using the HDBK/industry data base; however, these estimates are subsequently refined by the user based on the actual data. The methodology provided to enable the user to measure the ESS parameters (eg defect density, screening strength etc) is based on a curve fitting solution to the general ESS mathematical expression developed in Appendix A. These changes were made to eliminate the need for highly accurate data in the HDBK.

ii) For analysis and modelling purposes defects are segregated into errors and defects with defects being further subdivided into latent and patent defects. Since it is precipitated latent defects that determine the reliability in the field it is important to distinguish between errors and defects. Although the user must minimize and control errors, the improvements in these areas do not necessarily reduce latent defects nor improve reliability.

iii) The SPC control charts used for monitoring purposes were modified to show requirements that are based on and directly related to the customer's reliability requirements. In addition, the process mean is determined using regression analysis since the mean is expected to change as a result of corrective actions and continuous improvement. A modified form of PARETO chart is also recommended to help identify problems requiring analysis. The modification to the PARETO is to not only compare on the basis of frequency of occurrence but to relate the frequency to that expected based on the unit's complexity and the ESS predictions.

iv) The mathematical expression described in Appendix A is used to relate remaining defects (at ESS stress levels) to field reliability. This relationship requires prior knowledge of the average time constant in the field. Alternatively, if the actual stress levels are known, the precipitation efficiency equations can be directly applied. With either method, the original estimates are to be refined based on actual data.

v) The requirement for a failure free acceptance test (FFAT) was eliminated and replaced with an SPC program to measure and control remaining defects. The FFAT requirement was considered to be potentially damaging and uneconomical and tended to be contrary to ESS and the HDBK philosophy of defect elimination and control. A minimum verification test is used however so that ESS can not be entirely eliminated and tests remain in place to collect SPC data.

4.4 As part of the contract, LSL developed PC software to facilitate the implementation of the HDBK procedures. The software provided in the tool kit included planning software (344PLAN), data analysis software (344CURVE) and SPC software (344SPC and 344PARTO). A tool to assist in the planning phase ie 344CHART was also provided to prepare a multi level flow chart. This software and its operation was explained in a separate software users manual.

5. ILLUSTRATIVE EXAMPLE

This section illustrates the application of the HDBK methodology proposed in this report. The example makes use of the PC software developed for this study contract and contains example screens produced by the various programs in the tool kit.

5.2 In planning an ESS program it is necessary to determine the factory screening strength required to satisfy customer reliability requirements.

This is determined for a given design (ie. complexity) and level of maturity and is initially planned using HDBK 344 data or relevant experience data, and subsequently refined using actual data for the specific system. The basic steps for planning and implementing an ESS program are summarized in Table 5.1.

TABLE 5.1. ESS Planning Steps.

TASK	DATA
1. Determine initial defects per system	- Complexity of system - Defect Density for Parts and Workmanship - Limiting Constant Failure Rate (CFR)
2. Determine customer reliability	- MTBF and/or FFOP - Warranty or field defect costs - Operating life and field conditions
3. Define assembly and test restrictions	- Test Flow restrictions for integration calibration, contractual ATP
4. Determine required factory screening strength	- Precipitation Efficiency Equations Detection Efficiency
5. Optimize ESS selection and placement based on cost	- Cost model; test and rework fatigue damage assessment
6. Create goals and Performance Indices for Monitoring & TQM	
7. Refine Estimates of DIN, SS and update ESS Program based on Observed Results	- FRACAS data

5.2.1 To plan an ESS Program, the user must know

i) the required field MTBF (or failure rate), as specified by the customer

ii) the limiting failure rate of the system based on relevant data from similar equipments.

(iii) the system complexity defined in terms of the part types and reliability grades and the MIL-STD-2000 soldering and assembly complexity values.

5.2.2 For this example assume

i) the required field MTBF = 3400 hrs.

ii) limiting MTBF = 10,000 hrs. (CFR = 10^{-4})
the allowable MTBF due to latent defects is thus,
1/(1/3400 - 1/10000) = 5151 hrs.

The example uses 5500 to provide a safety factor.

5.3 Before performing any the calculations, the user must specify the modelling parameters eg fraction of RV and TC sensitive defects and the factory ESS stress adjustment factors for RV and TC, as illustrated in Figure 5.1.

5.4 The first step is to determine the estimated incoming defects per system. To perform this calculation the user defines the system parts and workmanship complexity for each assembly (i.e. complexity vector) and thus the complete system. (i.e. complexity matrix)

Figure 5.2 illustrates the loading screen for an example assembly and Figure 5.3 shows the complexity of a complete system.

5.4.1 The user then multiplies the complexity vectors by the defect density vector to determine the expected parts and workmanship defects relative to the application environment, in this example, AIF. Figure 5.3 shows the results of an example calculation.

Note that the displayed data includes the total system defects (i.e., 1.124) as well as the sum of the individual assembly defects. Because some assemblies have multiple usage on the system, the system defects can be greater than the sum of the individual assembly defects. Both values are useful for monitoring and control and were thus calculated. For the example shown, they are equal.

```
**************************************************************************
      C A L C U L A T I O N   P A R A M E T E R S

PERCENTAGE OF DEFECTS DETECTABLE BY RANDOM VIBRATION
                          0.25

DEFECTS PROPORTIONAL TO STRESS
      RV DEFECTS PROPORTIONAL TO  [ Grms actual / 6 Grms ]^N
                 N=           1
      TC DEFECTS PROPORTIONAL TO  [ Temperature Range / 120 DEG C ]^M
                 M=        0.05                  —   -

IMPROVEMENT FACTOR
      DEFECTS PROPORTIONAL TO [I]^(YEAR-1990)
                 I=        0.95          note: I<1
      Constant improvement factor =             1
**************************************************************************
      CURRENT YEAR IS                  1990
```

FIGURE 5.1. Example Modelling Parameters.

ASSY NO	123A1-1	QTY/Nxt ASY	1	SCREEN #	0
DESCRIPTION	PS 1	RV TEST EFY	0.5	TC TEST EFY	0 5
USED ON	123456A1-1	TEST $	$200	REWORK $	$1,000

PART/GRADE	S	B	B0	B1	C	C1	D
MICROCCTS	0	56	0	23	0	0	0
	S	TXV	TX	JAN	LWR	MISC	Plast
TRANSISTORS	0	41	0	19	0	0	0
DIODES	0	113	0	2	0	0	0
	S	R	P	M	L	MIL	LWR
RESISTORS	0	0	340	0	0	5	0
CAPACITORS	0	0	93	0	0	0	0

	MIL	LWR		MIL	LWR		ALL
MAGNETICS	1	0	RELAYS	5	0	ROTATE	0
CONNECTOR	4	0	SWITCH	0	0	MISC 1	0
			PWB	4	0	MISC 2	0

CONNECTIONS	PTH	PINS	LEADS	Ref TOT PARTS
	2958	430	2501	706

FIGURE 5.2. Example Assembly Complexity Data.

EQUIPMNT	EXAMPLE	ASSY DEF	1.124	PART DEF	0.806	WRK DEF	0.318
ENVIRON	AIF	ESS $	$1,000	DEF REMVD	0.000	DEF REMN	1.1236

PART/GRADE	S	B/TXV	B0/TX	B1/JAN	C/LWR	C1/MISC	D/Plast
MICROCCTS	0	284	0	261	0	0	0
TRANSISTORS	0	174	0	118	0	0	0
DIODES	0	374	0	40	0	0	0

	S	R	P	M	L	MIL	LWR
RESISTORS	0	0	1265	0	0	31	0
CAPACITORS	0	0	696	0	0	24	0

	MIL	LWR		MIL	LWR		ALL
MAGNETICS	5	17	RELAYS	12	0	ROTATE	0
CONNECTOR	31	0	SWITCH	0	0	MISC 1	0
			PWB	7	0	MISC 2	0

P.T. HOLE	9681	LEADS	14124	PARTS	3370	
PINS	2069					
ASSY #	17494	SOLDER #	25212	TOTAL WRK	42706	

FIGURE 5.3. Example System Complexity and Defects for AIF Environment.

The display also indicates the total test cost (at this stage without ESS) and the proportion of parts and workmanship defects.

Parts	=	.806/1.124	=	.72
Workmanship	=	.318/1.124	=	.28

5.5 The next step, is to determine the screening strength required to meet the customer required reliability.

5.5.1 The customers MTBF requirement is translated into a requirement for remaining defects. This calculation uses expression 2.2 with user specified values for t and K, in this example t=1000 Hr and K = 1/1000. The ratio of defects remaining to initial defects determines the screening strength required. If the detection efficiency is known then the precipitation efficiency can be calculated and the equations for precipitation efficiency solved to determine the required RV and TC as illustrated in Figure 5.4.

5.5.2 To determine the factory defect levels corresponding the field defect density, the user must apply a stress adjustment factor (SAF). The SAF relating the field and baseline stress is calculated by repeating the defect density calculations of 5.4 using the baseline stress (factory) environment, as shown in Figure 5.5, and taking the ratio of the defects per system at the field and baseline stress. For this example the SAF is 1.124/2.726 = 0.41.

5.6 To calculate the defects removed by ESS, the screening strength must be calculated as the product of the precipitation efficiency and the detection efficiency. Precipitation efficiency is determined using the equations given in the HDBK for the type of environment and stress levels used for ESS.. Detection efficiency (DE) considers the factors summarized in Figure 5.6. (Note that DE is low if testing is not performed concurrently with stress.) The defects removed are determined by multiplying the screening strength by the incoming defect density. This calculation should be performed separately for TC and RV defects.

```
******* ESS PLAN BASED UPON REQUIRED FIELD MTBF ******
          and CURRENT DEFECTS REMAINING

Required outgoing MTBF                  5000.00 Hrs/Def
Measured over                              1000 Hrs
Time constant in field                     1000 Hrs
Stress Adj Fctr      0.41
Current outgoing DEF/SYS                 2.7264 DEF/SYS at Factory Stress
Maximum outgoing DEF/SYS                 0.288 DEF/SYS at Field Stress
                                         0.7015 DEF/SYS at Factory Stress

Required Screening Strength =              0.743
Detection Effy       0.9 Required Precipitation Effy =       0.825

RV Screen Parameters
   For Grms of         6 Grms       Required time [min]      17.7

TC Screen Parameters
    For Temperature range     120 C
    and   Transition rate       3 C/Min Required cycles      10.9
```

FIGURE 5.4. Example Calculation of Maximum Allowable Defects Remaining and Required Minimum Screening Strength.

```
EQUIPMNT   EXAMPLE ASSY DEF   2.726 PART DEF   2.163  WRK DEF  0.563
ENVIRON    FACTORY  ESS $    $1,000 DEF REMVD  0.000 DEF REMN 2.7263

PART/GRADE     S      B/TXV     B0/TX    B1/JAN    C/LWR    C1/MISC D/Plast
MICROCCTS          0     284         0       261        0          0       0
TRANSISTORS        0     174         0       118        0          0       0
DIODES             0     374         0        40        0          0       0
                   S       R         P         M        L        MIL     LWR
RESISTORS          0       0      1265         0        0         31       0

CAPACITORS         0       0       696         0        0         24       0

                 MIL     LWR                 MIL     LWR                 ALL
MAGNETICS          5      17 RELAYS           12       0 ROTATE          0
CONNECTOR         31       0 SWITCH           0        0 MISC 1          0
                             PWB             7        0 MISC 2          0

P.T. HOLE       9681         LEADS        14124          PARTS        3370
PINS            2069
ASSY #         17494         SOLDER #     25212          TOTAL WRK 42706
```

FIGURE 5.5. Example System Complexity and Defects for Factory (Baseline) Stress.

TEST DETECTION EFFICIENCY FACTORS		
**********		
FUNCTIONAL TEST or FUNCTIONAL & PARAMETRIC	[.5 -.8] [.8 - 1]	0.90
TESTING AT AMBIENT or CONCURRENT WITH STRESS	[.2 -.6] [1]	0.59
FAULT ISOLATION & REWORK -FAULT ISOLATION -REWORK & REPAIR -OTHER DEFECT CREATED	[.8 - 1]	0.95
ESTIMATED DETECTION EFFICIENCY		0.504

FIGURE 5.6. Example Test Detection Efficiency Calculation.

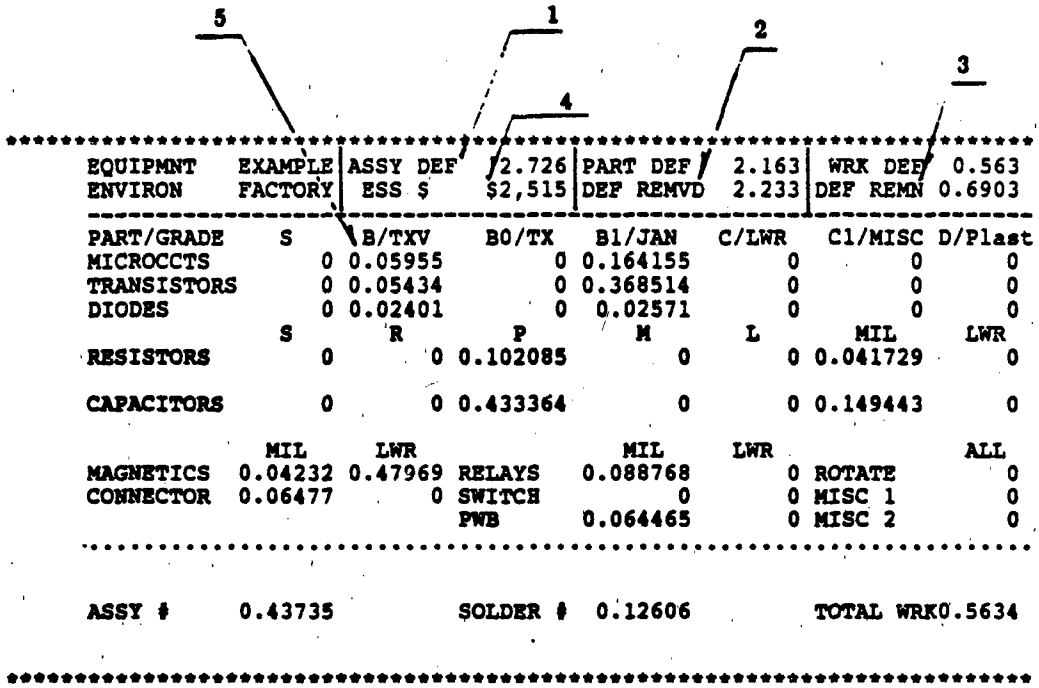
5.7 The ESS plan as designed above would meet reliability requirements but would not be optimized for cost. Assemblies with high screening cost ie cost of removing a defect, should be considered as candidates for module level or special assembly level ESS. Adding ESS at lower levels and repeating the planning process in an iterative manner determines the cost optimized ESS plan with consideration for the integration, calibration and functional testing restrictions required to manufacture the product. An example of an optimized ESS program is illustrated in Figure 5.7. Note that the system complexity has been converted into defect densities (DPU) for the various parts and complexity factors. These values as well as those for total defects and defects removed would be used as requirements for SPC.

5.8 Equation 2.2 can then be used to verify that field reliability (MTBF) will be achieved and to estimate the FFOP. The results of such a calculation are illustrated in Figure 5.8.

5.9 To ensure that the ESS program is not too stressful and does not consume too much of the useful (fatigue) life, the user computes damage factors for RV and TC. The life capabilities can be determined from design requirements, qualification test, or the anticipated end application. These calculations are illustrated in Figure 5.9.

5.10 Actual production data would be subsequently analyzed to refine the screening strength and defect density estimates. This is accomplished by curvefitting the defect removal distribution to expression 2.2, and is illustrated in Figure 5.10.

5.11 SPC would be used to monitor and control the critical ESS parameters ie defects remaining, defect density, screening strength, defects removed and cost etc. Illustrative SPC and PARETO charts are shown in Figures 5.11 and 5.12. Note that these charts included the requirements as well as actual and statistically expected variation.



1 Sum of Def/Assy at baseline stress, excluding effect of multi-usage assy's.
2 Total defects removed at actual ESS stress, including effect of multi-usage assy's.
3 Defects remaining at baseline stress, including effect of multi-usage assy's.
4 Cost of ESS, including normal testing.
5 Defects per system due to indicated part & grade.

FIGURE 5.7. Example Defects Removed and Remaining and ESS Goals for Optimized Plan.

F I E L D M T B F

	Factory Stress	Field Stress
DEF(remaining) latent	0.619 Def/Sys	0.254 Def/Sys
DEF(remaining) patent	0.071 Def/Sys	- Def/Sys
STRESS FACTOR (FIELD/FACTORY)	0.41	
Constant Failure Rate (field stress)		1.00E-04 Def/Hr
Field time constant		1000 Hrs

OPERATING HRS	Dpat	Dlat	Dcfr	Dtot	MTBF	% FFOP
10	0.071	0.003	0.001	0.074	135	92.85%
100	0.071	0.024	0.010	0.105	954	90.05%
200	0.071	0.046	0.020	0.137	1464	87.23%
300	0.071	0.066	0.030	0.166	1803	84.67%
500	0.071	0.100	0.050	0.221	2267	80.21%
1000	0.071	0.160	0.100	0.331	3020	71.81%
3000	0.071	0.241	0.300	0.612	4904	54.24%
5000	0.071	0.252	0.500	0.823	6077	43.92%

% Defect Free Systems, excluding CFR effect is 72%

FIGURE 5.8. Example Calculation of Expected Field MTBF and FFOP.

F A T I G U E L I F E DAMAGE INDEX D = N S^B

****

TEMPERATURE CYCLING [B=2.5] B= 2.5

	LIFE		ESS	
N= No of cycles	N1=	7300	N2=	50
S= Temp Range	S1=	30	S2=	120

% of useful life consumed by ESS = 21.9%

RANDOM VIBRATION [B=6.4] B= 6.4

	LIFE		ESS	
N= Duration [min]	N1=	2E+06	N2=	5
S= Level GRmS	S1=	1	S2=	6

% of useful life consumed by ESS = 27.3%

REF: A. CRANDALL - RANDOM VIBRATION, PUBLISHER - JOHN WILEY & SONS, NY
B. ENGELMAIER - EFFECTS OF POWER CYCLING IN LCC - BELL LABORATORIES, NJ

FIGURE 5.9. Example Fatigue Life Calculation.

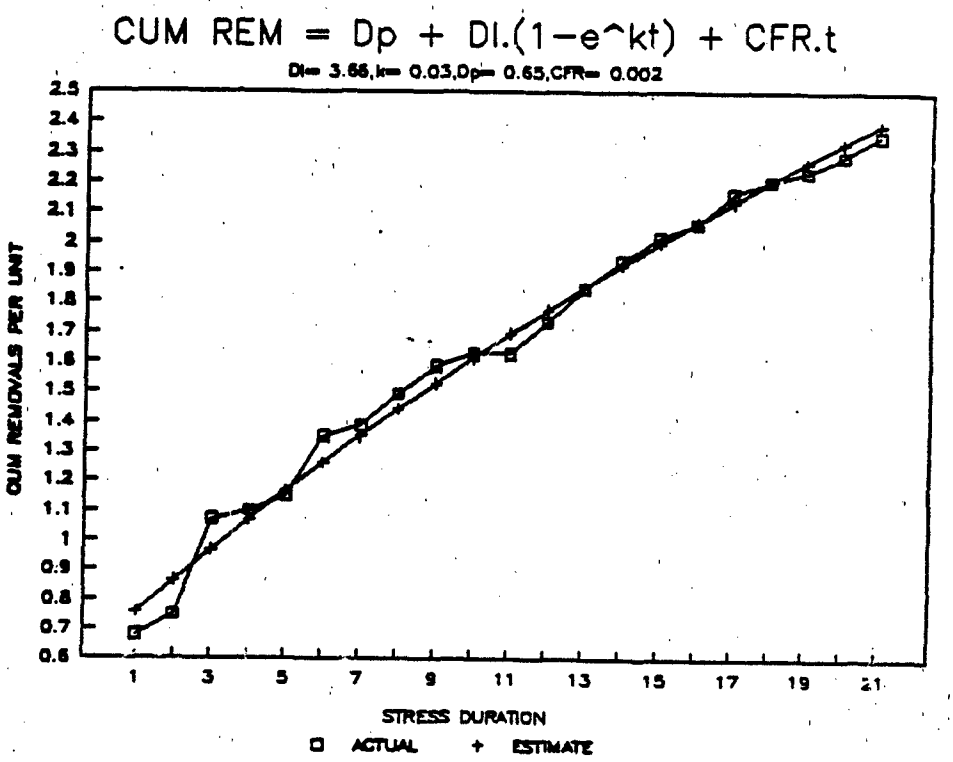


FIGURE 5.10. Example Curvefitting Solution of Factory Data.

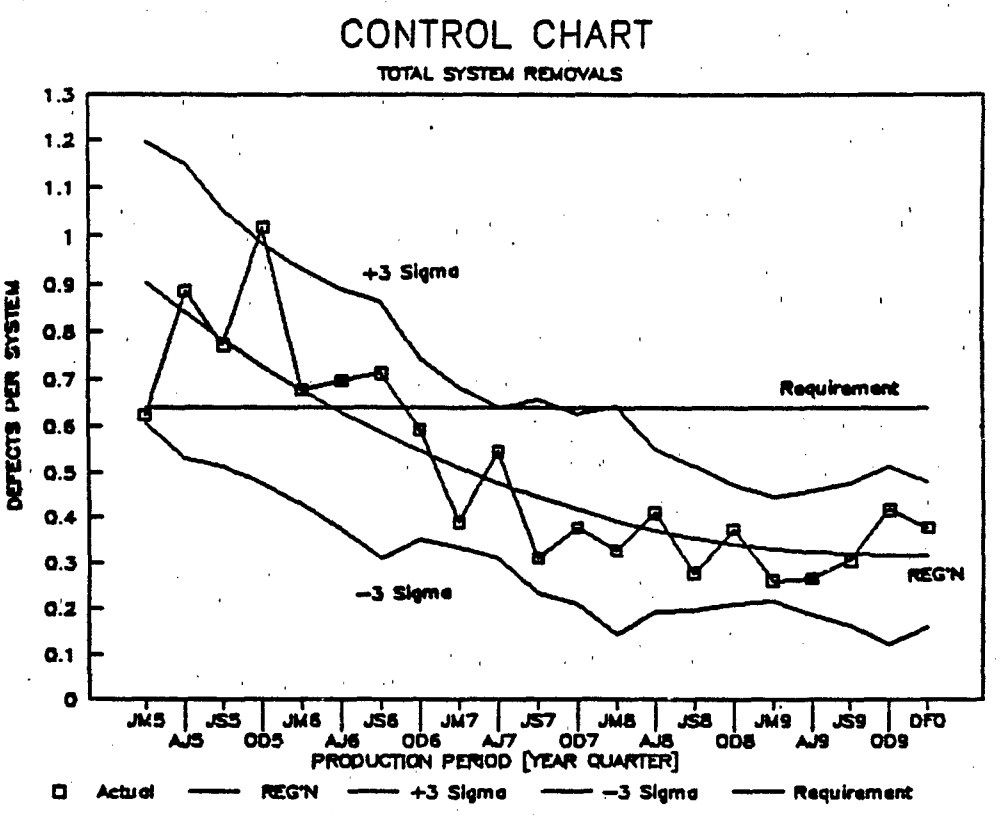


FIGURE 5.11. Example SPC Chart.

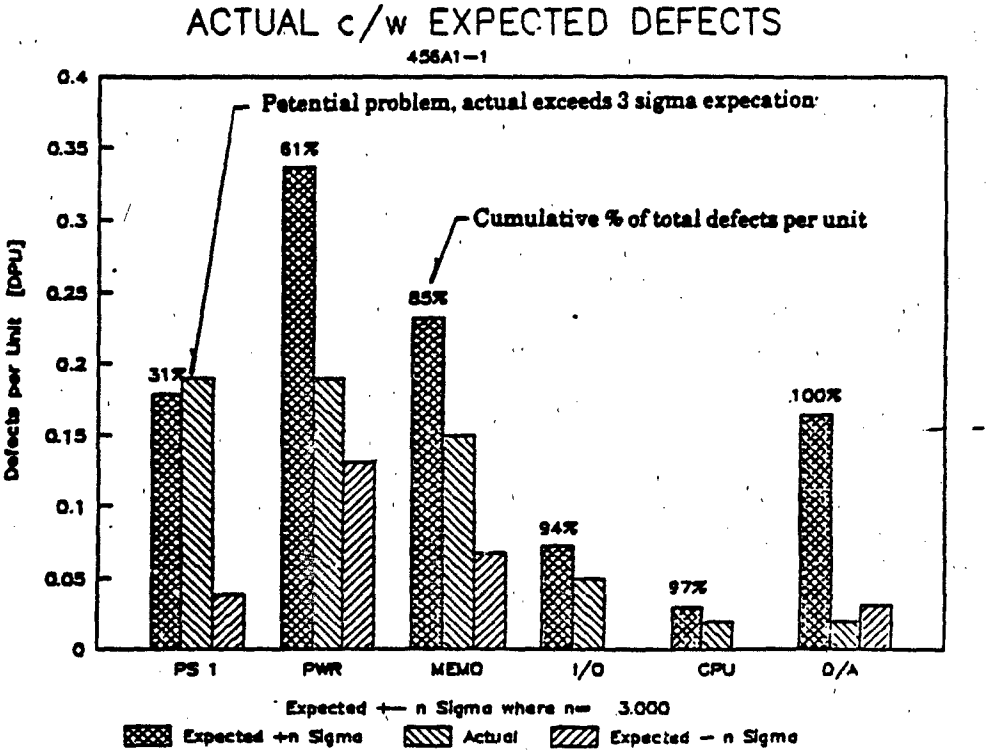


FIGURE 5.12. Example PARETO Chart.

6. CONCLUSIONS

The methodology of DOD HDBK 344 was successfully applied to three different types of equipment in an actual factory environment. The equipments were designed by different companies and were in manufacture at LSL on a build to print basis and thus represented a larger cross section of military electronic hardware and designs. Although the basic methodology of the HDBK was verified in this study, the detailed procedures needed modification to be practical and to improve modelling accuracy. The rationale and details of these changes were discussed in this report and are reflected in recommended changes to the HDBK and PC software developed under this study contract to facilitate ESS implementation.

In making the recommended changes, the level of accuracy required of the HDBK and the complexity of the model were kept in perspective and minimized by incorporating changes that allowed the maximum use of user and industry data. Recognizing the rapid advances in technology and associated changes in defect densities, the accuracy of HDBK tables should be sufficient for initial prediction and planning purposes only, with higher levels of accuracy being achieved using actual data to refine the estimates. Many of the modelling changes had the intent of preventing the inadvertent misapplication of the HDBK and included the partitioning of defects into RV and TC sensitive populations and the inclusion of a stress adjustment factor in the general model. Nonetheless, many of the generic observations cited in the HDBK as well as the precipitation efficiency equations demonstrated reasonable correlation with the observed findings.

Historically, failure mechanisms that have occurred early in the field have been of a similar nature and cause as those found through factory ESS. The HDBK's use of ESS to stimulate and either eliminate the cause of the defect mechanisms and/or control the magnitude (defect density) are inherently fundamental to providing the field with reliable electronic hardware. The quantitative approach provided by the HDBK is a viable methodology for providing assurance that field reliability will be achieved and provides TQM with the necessary capability to establish factory requirements that can be measured and directly related to customer's measures of satisfaction.

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APPENDIX A

A.1. INTRODUCTION

A.1.1 This Appendix describes the aspects of Environmental Stress Screening [ESS] theory and modeling that are fundamental for an effective ESS program.

A.1.2 The following aspects of ESS modelling are addressed:

i)	Basic ESS model	Paragraph A.2
ii)	Test Detection Efficiency	Paragraph A.3
iii)	ESS model	Paragraph A.4
iv)	Effect of increased stress	Paragraph A.5
v)	Concept of Stress Hardening	Paragraph A.6
vi)	Conclusions	Paragraph A.7

A.2. BASIC ESS MODEL

A.2.1 For ESS to be a viable methodology, it is necessary that the screening strength of a screen be independent of the number of defects. Also the screening strength must be independent of when the screen is performed and the screening strength of n screens of duration δ must be the same as one screen of duration $n\delta$.

A.2.2 Mathematically, these requirements can be satisfied if the defects are exponentially distributed in time.

$$D_x = D_l(t)(1 - e^{-K\delta})$$

where D_x is defects precipitated
$D_l(t)$ is latent defect population at time t
K is stress factor
δ is screen duration

A.2.2.1 Since $D_l(t)$ is the latent defects remaining at time t
then $D_l(t) = D_{initial}\, e^{-Kt}$ where $D_{initial}$ is the number of latent defects at time = 0.

$\therefore$ $D_x = D_{initial}\, e^{-Kt}\,(1 - e^{-K\delta})$ for all t and the screening strength is given by

$$1 - e^{-K\delta}$$

Thus, for the exponential distribution, screening strength is independent of t and is given by $1\text{-}e^{-k\delta}$

A.2.3 The other fundamental requirement for ESS is that the screening strength of n screens of duration δ must be the same as one screen of duration $n\,\delta$.

Assuming the exponential model, the screening strength is $1 - e^{-K\delta}$.

The screening strength of n successive screens is thus

$$1 - (1 - (1 - e^{-\delta t}))^n = 1 - e^{-n\delta t}$$

This is the same as the screening strength of duration $n\delta$; hence, the exponential model satisfies the fundamental requirements for ESS.

A.2.4 A direct consequence of this model is that the latent defect population has a constant hazard rate K

$$\text{Hazard rate} = \frac{\text{Failure rate}}{\text{Population remaining}} = \frac{\frac{d}{dt}\left[D(1 - e^{-Kt})\right]}{D - D(1 - e^{-Kt})} = \frac{DK\,e^{-Kt}}{De^{-Kt}} = K$$

A.2.4.1 Assuming that the defect rate of the normal (good) population is constant i.e.

$$MTBF = \frac{1}{\lambda g};\ \lambda g = \text{constant} = NC$$

where N is the complexity factor determined from the number of parts and workmanship operations and C is the defect density for each of the complexity factors.The defect rate of the combined 'good' and 'bad' populations is given by:

$$\text{DEFECTS REMOVED} = D_1(1 - e^{-Kt}) + NCt$$

$$\text{hence the defect rate} = \frac{d}{dt}(\text{Defect Removed})$$

$$= D_1Ke^{-Kt} + NC$$

i.e., the defect rate decays exponentially with time and is asymptotic to NC.

It should be noted that this result is the same as the CDE model given in the handbook; however, whereas the CDE model assumes a λg and λb, this derivation is based only upon fundamental and essential requirements for ESS.

A.2.4.2 If ESS is to be mathematically described by screening strength, it is necessary to verify that defect precipitation is exponential. The curve fitting analysis performed in the study contract did verify that the exponential distribution is a reasonable representation of the actual conditions.

A.3. TEST DETECTION EFFICIENCY

A.3.1 Assuming that defects have been precipitated, it is necessary to detect (i.e., observe) the defect.

The test detection efficiency DE is essentially a measure of the ability to detect a patent defect and hence assumes a degree of controllability of the affected circuitry and observability of the defect.

A.3.1.1 In practice, the controllability and observability are a function of

i) system design and application

ii) test equipment

iii) test environment

A.3.2 An important consideration is that defects may appear to be intermittent and also, what constitutes a defect for one system/application may not appear to be a defect in another, eg., FMECA. As heuristic examples consider the following:

i) catastrophic failure (open) of a capacitor may not adversely affect performance if the capacitor is used for redundant power supply filtering; however, the same capacitor used in a timing application could cause system failure.

ii) a broken lead or cracked solder joint may increase in resistance or open circuit (momentarily) with temperature and/or vibration. If the connection is part of a high impedance path or a heavily filtered, low frequency signal path, performance may not be degraded; however, the same defect involved in high speed data transmission or clock signals could cause system failure.

iii) soft (i.e., momentary) errors such as those that occur in memories or data transfer, may not be perceived as a problem in a display application eg. cause an imperceptible flicker on a display, but could be a failure in a navigation system where parametric accuracy is important or if the signal were used for control purposes eg. system shut down, etc.

In each of the 3 foregoing examples, it should be noted that the failure could be repeatable and easily detected or be of an intermittent nature.

A.3.3 These examples serve to illustrate that:

i) fault detection may require extended testing to detect and isolate the fault.

ii) fault detection may require environmental stresses eg. vibration, temperature, temperature change.

iii) the detectability of the fault is a function of the

a) type and application of the equipment

b) the ability of the test equipment to exercise the necessary function i.e., controllability and to detect the failure i.e. observability.

iv) the recognition of a defect is influenced by its criticality.

A.3.4 An additional consequence is that two systems with the identical complexities and exposed to identical screens could appear to have different latent defect populations because of the following:

i) equipment type and purpose/function

ii) type of test equipment

iii) nature of test

and iv) criticality of defect(s)

A.3.5 Mathematically, the time dependency aspect of detection efficiency would appear to lend itself to a Poisson distribution.

$DE = DP(1 - e^{-K2t})$ were DP (the probability of detection) and K2 (the detection stress constant) are measures of the inherent test detection capability.

A.3.6 Considerations not directly related to detection efficiency but affecting its perception are:

i) the ability to isolate and repair defect, and

ii) the ability to repair the defect without introducing additional defects.

A.3.7 The factors to be considered in assessing test detection efficiency are summarized in Table A.1.

TABLE A.1. Factors Affecting Test Detection Efficiency.

Probability of Occurrence.

Fault Detection (with and without concurrent stress).

Test Duration (with and without concurrent stress).

Fault Isolation.

Repair/Rework defect creation density.

A.3.8 For effective fault detection, extended test times under varying stress types, eg. RV, TC, etc., are required in conjunction with test equipment capable of exercising all functions and observing any defects. Subsequent to fault detection, the defect must be isolated and repaired without introducing additional faults.

A.4. MORE COMPLETE MODEL

A.4.1 The problems associated with defect precipitation and detection become interrelated since the same environmental stresses necessary to precipitate a defect are also involved in its detection. In other words, during defect detection, defect precipitation is also occurring, and vice versa.

A.4.2 This can be expressed mathematically as the convolution of the precipitation and detection functions.

A.4.2.1 Assuming precipitation as a function of stress level (K) and duration (t) is given by $D_x(t,K) = D_l(1 - e^{-Kt})$ and detection is given by

$D_E(t,K) = D_p(1 - e^{-K_2 t})$ then the observed defect rate is given by

$D_I(1 - e^{-K_1 t}) * (D_p(1 - e^{-K_2 t})$ where *denotes convolution

A.4.2.2 To solve this it is convenient to use the fact that convolution in the time domain is the inverse Fourier (or Laplace) transform of the product of the Fourier (or Laplace) transforms of D_x and DE

$$\text{Defect rate} = F^{-1}[F(D_x)\,F(DE)]$$

A.4.3 At this point, it is useful to observe the analogy to electronic signals. In essence, defect removal has two aspects; a precipitation term that is analogous to a generation term and a detection term that is analogous to a (low pass) filter term.

A.4.4 The following conditions are appropriate for ESS modelling and are solved in Table A.2.

i) detection of an existing precipitated defect population eg. testing after non-operating screen,

ii) detection of defects precipitating with an exponential distribution i.e., during ESS.

ii) detection of detects precipitating with a constant rate i.e., due to limiting MTBF of System (design).

A.4.5 The more complete ESS model requires the summation of the 3 terms identified above and is as follows:

$$D_{REMOVED} = D_{E1}D_P(1 - e^{-B_1 t}) + D_{E2}D_I\left[1 - \frac{B_2}{B_2 - A}e^{-At} - \frac{A}{A - B_2}e^{-B_2 t}\right]$$

$$+ \frac{D_{E3}D_C}{B_3}\left[e^{-B_3t} + B_3t - 1\right]$$

D_p = EXISTING PATENT DEFECTS AT START OF ESS

D_l = LATENT DEFECTS AT START OF TEST

D_c = 'CONSTANT FAILURE RATE' DUE TO A LIMITING MTBF.

D_E = TEST DETECTION EFFICIENCY

B = TEST DETECTION EFFICIENCY 'K' FACTOR

A = ESS DEFECT PRECIPITATION 'K' FACTOR

NOTE:

The subscripts 1,2 and 3 refer to patent, precipitating latent, and constant failure rate effects respectively.

TABLE A.2. Mathematical Expression for ESS.

ESS	GENERATION TERM TIME DOMAIN	GENERATION TERM LAPLACE TRANSFORM	DETECTION TERM LAPLACE TRANSFORM	TIME DOMAIN RESPONSE
DETECTION OF EXISTING POPULATION OF PATENT DEFECTS	D	$\frac{D}{S}$	$\frac{B}{S+B}$	$D(1-e^{-Bt})$
DETECTION OF DEFECTS PRECIPITATING WITH AN EXPONENTIAL DISTRIBUTION	$D(1-e^{-At})$	$\frac{DA}{S(S+A)}$	$\frac{B}{S+B}$	$A \neq B, D[1-B\frac{e^{-At}}{(B-A)}-\frac{A\,e^{-Bt}}{(A-B)}$
				$A = B, D[\|1-e^{-At}[At+1]]$
DETECTION OF DEFECTS PRECIPITATING AT CONSTANT RATE (i.e. Constant λ)	Dt	$\frac{D}{S^2}$	$\frac{B}{S+B}$	$\frac{D}{B}[e^{-Bt}+Bt-1]$

A.4.5.1 The effect of these equations was shown in Part B Figures 2.9 and 2.10.

A.4.6 In this model, the effect of defects in the replacement population is inherently included in the exponential rate model.

A.5. EFFECT OF INCREASED STRESS

A.5.1 Assume that latent defect removal can be modeled mathematically as follows

$$D_{REMOVED} = D_I(x)(1 - e^{-tK(x)})$$ where $D_I(x)$ total latent defects, $K(x)$ is stress factor, t is stress duration, and x is stress level.

A.5.2 Increasing stress can then have the 3 possible effects indicated in Table A.3.

TABLE A.3. Effect Of Increasing Stress on Defects and 'K'.

Possibility	Total Latent Defects	K	Comment
A	Increase	Increase	Most General
B	Increase	No change	Unlikely/ESS Impractical
C	No change	Increase	Simplest to apply

A.5.3 Consider first possibility A since this is the most general case from which possibilities B and C can be derived. With this possibility, increasing the stress level increases both the total number of latent defects and the precipitation factor K.

A.5.3 Defect mechanisms that lend themselves to this model (possibility A) are mechanical type failures due to stress or fatigue limits. Due to the multitude of connections, joints and members in the equipment, each with a

possibility of various imperfections, the equipment will experience increased failures as the stress level increases towards the stress/fatigue limits of the imperfections.

A.5.4 Possibility B, which has only latent defects increasing with stress level would mean that ESS is ineffective since the defect precipitation rate can not be accelerated by applying a higher stress level. This hypothesis can be rejected based on available evidence that indicates that precipitation can be accelerated.

A.5.5 Possibility C has a fixed number of latent defects (for stress levels kept within design capabilities); however, the precipitation rate can be accelerated by increased stress.

Many defect types lend themselves to this model. For example reactions with acceleration factors that have an Arrhenius relationship i.e. acceleration factor of

$$e^{\frac{-Ea}{Kt}}$$

apply since the failures would occur, regardless of stress level, and are only accelerated by increased stress.

In general, all reaction rates that increase with temperature are included in this group. Failures resulting from chemical reactions, corrosion, intermetallic formation, diffusion, leaks, or contamination ingress,etc., should thus lend themselves to this ESS model (Possibility C).

A.5.6 Both models A & C thus have technical merit and need to be used in ESS modelling, with A representing the most general case.

The consequences of Model A are that increasing stress causes increased defects (beyond what is necessary or would occur in the end application) which have a repair cost that affects the economical optimization of an ESS program.

A.6. THE CONCEPT OF STRESS HARDENING

A.6.1 Stress Hardness. To provide insight into defect precipitation and thus the validity of various ESS models and assumptions, the concept of 'STRESS HARDENING' has been developed. Stress hardening assumes that defects have a distribution in strength (for each stress type). Qualitatively this can be explained as follows:

i) Defects with a low strength precipitate quickly under low applied stress, eg., infant mortality.

ii) Defects with greater strength require higher stress or longer time to precipitate.

Stress hardening thus involves removing defects below a stress level such that they do not (readily) precipitate in the field. Stress hardness is thus the ability to withstand a given stress level, as measured by the defect precipitation rate.

A.6.2 Stress Hardness Model. The Stress Hardness Model assumes that flaws have a distribution in strength and that under an applied stress, the flaws weaken and migrate to lower strength levels according to an Arrhenius relationship.

$$e^{-\frac{Ea}{Kt}}$$

Defects with no residual strength are patent defects.

An example of a stress hardness analysis is provided in Figures A.1.

Figure A.1 is the result of a uniform distribution in stress and wear out populations. Note the general shape of the familiar 'bath tub' curve and that the initial reduction in defect rate is nearly exponential. Subsequent to the flat, constant failure rate period, the failure rate increases due to wear out. The first wear out affects only part of the population, the second wear out is more extensive.

A.6.6.3 In practice, every interconnect and joint ,etc., will have a multitude of possible failure mechanisms with varying stress hardness capability. The total number of defects possible within a system thus becomes very large.

A.6.6.4 Depending upon the defect distribution, the model predicts that the defect rate decreases with time and is asymptotic tc a limiting defect rate that is a function of the stress level. This is consistent with the models developed in paragraphs 2 and 4 and generally accepted reliability theory.

A.7. CONCLUSIONS

A.7.1 From the discussion paper, several aspects of ESS modeling and analysis have been addressed that affect the perception of screening effectiveness and/or ESS prediction accuracy.

A.7.2 The precipitation and detection of defects can be modeled as in paragraph A4.

A.7.2.1 Since both defect precipitation and detection are exponential, the perception of screening strength may be a measurement of detection efficiency, depending upon which K term dominates.

A.7.2.2 Since stress and time are required for defect detection, the value and economics of lower level ESS need to be assessed.

A.7.3 The estimation of test detection efficiency is as important as the need to estimate precipitation efficiency. Test detection efficiency, however, is affected by several considerations, as discussed in paragraph A3 and is not trivial.

A.7.4 A proper ESS model recognizes that (certain types of) latent defects increase with stress level. A priori knowledge of the defect vs. stress distribution is thus necessary.

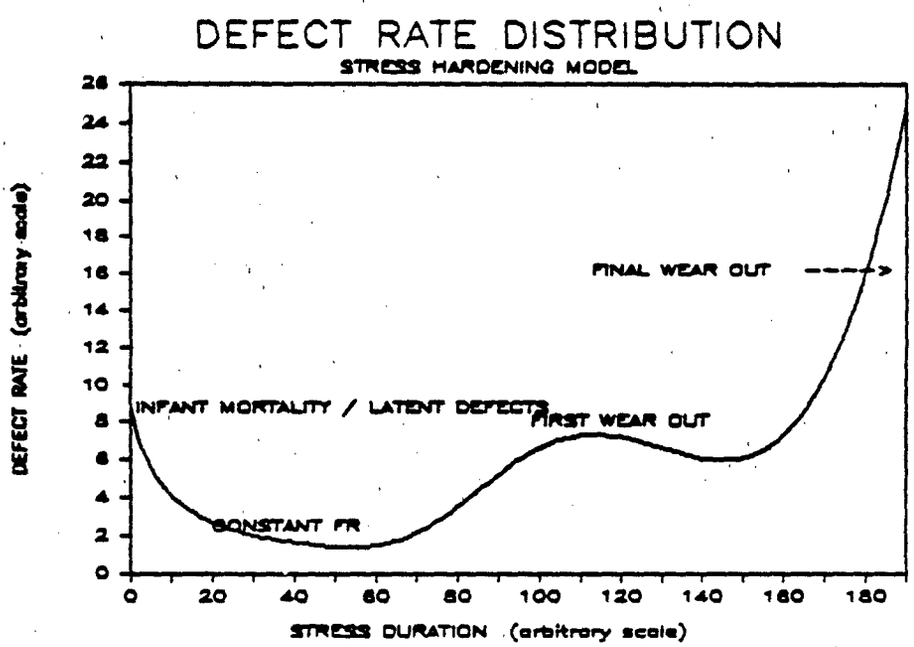

FIGURE A.1. Stress Hardness Model, Flaws with Uniform Distribution in Strength and Wear Out Populations.

A.7.5 The perception of defects is affected by the type and design of the equipment and how it is used and tested. Thus equipment with similar complexities may appear to have different latent defects depending on the testing and application.

A.7.6 The concept of stress hardening tends to explain observed ESS and reliability effects from a simple model and could be a useful tool or concept for ESS modeling. The model predicts that flaws will have a temporal distribution. If the stress is high with respect to the flaw strength then a certain flaw size will cause failures that have a normal distribution in time becoming log normal for greater flaw strengths. This prediction of the model is consistent with the literature that indicates that failures often have a log normal distribution in time. This means failures are not random but are caused by a definite defect mechanism that has both a strength distribution and temporal distribution when under stress.

A.8. DEFECT TYPES AND DEFINITION

A.8.1 For consistent ESS modelling and terminology, it is necessary to examine the definition of defects based upon type and impact on ESS. In general defects belong to 2 major groups, latent and patent.

A.8.1.1 LATENT DEFECT: defect that has the potential of eventually causing a failure, i.e., flaw with a residual strength.

A.8.1.2 PATENT DEFECT: defect that has the potential of immediately causing a failure, i.e., flaw with no residual strength.

NOTE:

It should be noted that not all latent nor patent defects will necessarily cause a failure.

A.8.2 Latent Defects for ESS purposes are of 2 types.

A.8.2.1 Stress dependent latent defects. Latent defect that precipitates as a patent defect only if a threshold stress is exceeded. The existence of stress dependent latent defects results in an increasing number of defects with increasing (ESS) stress levels. Because ESS inherently involves different stress levels and stress level tradeoffs, it is fundamentally necessary to be able to model and predict this type of defect (i.e., Possibility A in A.5).

A.8.2.2 Stress Independent Latent Defects. Latent defect that precipitate as a patent defect regardless of stress level. Increasing stress has the effect of accelerating the time to failure; however, the total quantity of defects does not increase (i.e., Possibility C in A.5).

A.8.3 Patent defects need to be considered based upon their origin and detectability. Patent defects that are due to assembly and workmanship 'errors' must be distinguished from patent defects due to precipitated latent defects. The purpose of ESS is to i) identify (and thereby possibly eliminate through corrective action) the latent defect cause and ii) reduce the number of latent defects through screening and thereby reduce the failure rate.

i) Errors. Errors are patent defects that are caused by workmanship and are readily detected and removed by simple testing or inspection. ESS is thus not required to detect and eliminate errors and thus errors have only an indirect effect on reliability due to rework.

   Errors should be preventable and should not occur whereas patent defects arising from latent defects are only preventable to the limits of the state of the art in technology and equipment.

   Although errors should be monitored using SPC and efforts taken to eliminate them, the data and associated SPC should be separated from patent defects resulting from a latent defect.

ii) Patent Defects. Although errors are also a subset of patent defects, for terminological simplicity, patent defects can be considered as only those resulting from latent defects.

A.8.4 Using the suggested definition of patent defects, ESS modelling needs to recognize 2 types as determined by their detectability.

i) Stress Detectable Patent Defects. Defects that although having no residual strength cannot be detected without the application of stress and time. Examples include fractured wires making (intermittent) contact, etc. Detection of these defects requires testing concurrent with stress application.

ii) Immediately Detectable Patent Defects. Defects that can be detected without requiring stress, provided the proper test is performed.

A.8.5 Although perhaps appearing complex in definition, it is important that the above types of defects be recognized in ESS. From a practical aspect, though, it is recommended that the defect definition be simplified and combined as shown in Table A.4.

TABLE A.4. Defect Definition Simplification.

ESS DEFECT	SUGGESTED HDBK DEFINITION	COMMENTS
LATENT, STRESS DEPENDENT	LATENT	Combine all 3 defect types provided HDBK models stress dependent flaws. From a practical aspect, stress detectable patent is equivalent to a latent defect
LATENT, STRESS INDEPENDENT		
PATENT, STRESS DETECTABLE		
PATENT, ERROR	ERROR	
PATENT, IMMEDIATELY DETECTABLE	PATENT	

A.8.6 Screenable Defect.

A.8.6.1 From a practical aspect, a defect (mechanism) should be only considered screenable if precipitating the defect reduces the failure rate. From a causal aspect, this would mean that a non screenable defect would be one that the stress required to remove that flaw would cause the strength of a lesser flaw to be degraded, such that there would be no net improvement.

Because of this effect, continued ESS approaches a screening limit, beyond which failure rate is not improved even though defects are being removed.

This effect is predicted and demonstrated by the stress hardening model of paragraph A5.6.

It is also illustrates that for optimum reliability the design and manufacturing processes must be proper and controlled, and that there is a limited reliability that can be achieved through screening alone.

A.8.7 Relevant and Non Relevant Defects. ESS can remove defects that improve field reliability; hence, these defects are relevant . Because of stress dependent latent defects and the screening limit, ESS can remove defects that do not improve field reliability, i.e., would not have occurred under field stress conditions; hence, these defects are non relevant. It is necessary that ESS modeling predict and separately track relevant and non relevant defects. Non relevant defects resulting from stress levels that are too high (and possibly damaging) increase the production cost due to rework and influence ESS optimization and stress limitations. From a practical aspect, the ESS estimate of latent defects should include only relevant defects , i.e., defects above the screening limit.

APPENDIX B

DOD-HDBK-344 Software Toolkit and User Manual

B.1 Description: DOD-HDBK-344 contains procedures for the planning, monitoring and control of a cost-effective ESS program. These procedures and associated data bases for part, assembly, and soldering defect densities, equations to calculate screening strength, and tools for preparing multilevel flow charts, curvefitting actual data, and preparing SPC and PARETO diagrams have been incorporated into a suite of PC software programs. This software runs in a LOTUS 1-2-3 environment and operates interactively with the user. The user interface is through user friendly menus and screens that are controlled and created by LOTUS macros that operate transparently to the user. In this mode, a comprehensive understanding of LOTUS 1-2-3 is not required. If the user is familiar with LOTUS, some of the executions can be performed directly from LOTUS if desired. The software can thus be used by personnel with a minimum of experience on PC computers and LOTUS 1-2-3, and is offered in a spreadsheet environment that is widely used throughout industry. The software toolkit for implementing all of the procedures of DOD-HDBK-344 is made up of the following programs:

(a) 344MMASTR
(b) 344PLAN
(c) 344CHART
(d) 244SPC
(e) 344CURVE
(f) 344PARTO

Each of the programs described below is a shell that contains the necessary equations, viewing screens, and macros for both specific execution steps and operator interface. Data required by the program, (e.g. factory defect data etc.) are loaded into the worksheet shell from flat (ASCII) files, other worksheets, and/or by direct user interface. The program performs the necessary data manipulations and calculations and creates output data files for use by the operator or other 344xxx software programs. These files can be text files or other worksheets depending on the application. File transfers are commanded by the user, but the type of file, etc. is transparent to the user with the program determining the necessary type of file and its structure.

344MASTR is the control program that guides and instructs the user on which program to use for specific tasks. The working program listed above can be called up and loaded directly from 344MASTR. A brief discussion of ESS and introductory help screens on the purpose and use of 344xxx programs are also provided.

344PLAN is the program used to plan and optimize the ESS program. This program implements Procedures A, B and C of DOD-HDBK-344. The program contains help screens on the basic operation of the program and contains utility modules for estimating field reliability, determining damage indices, and estimating detection efficiencies. The program calls up selected records from the data base of part, assembly and soldering defect densities (PPM) that are contained in the data base file DEFDENSI(ty).WK1.

The program is used during the initial planning phase and on a continual basis to refine the ESS program and to ensure that it remains optimum. The program creates output data files containing the goals and requirements for parts and manufacturing defects for each assembly and level of integration-test.

344CHART is used to produce a multilevel flow chart showing defects entering and removed at each assembly screening level. The chart produced by this program provides the framework for screen selection and placement optimization. Defects introduced, removed and remaining are shown for each assembly at all integration test levels. Random vibration (RV) sensitive and temperature cycling (TC) sensitive defects are displayed separately on the same diagram. Screening and test costs are also indicated to help identify high cost screens that could possibly be more cost-effectively performed at an earlier stage. The data for this program is created by 344PLAN.

344SPC is used to prepare statistical process control (SPC) charts and implements DOD-HDBK-344 Procedure E. These are modified SPC charts that compare present performance capability with requirements that relate to the required field reliability. The charts thus indicate requirements, show the present level of performance (capability), and the statistically expected variation due to limited lot size. The process capability is automatically determined by the program through a polynomial regression analysis of the actual data. The data for this program is loaded from actual factory or field data either manually or from a separately prepared data file.

344PARTO is used to prepare PARETO diagrams for any desire integration test level. These are modified PARETO charts in that actual results are not only compared on the basis of relative frequency of occurrence, but also with consideration for the expected frequency based on the relative complexity and the established goals and requirements. The requirements data base is created and updated on a continual basis using 344PLAN. The actual factory data are loaded manually or from a separately prepared data file.

344CURVE is used to analyse actual factory or field data using a curve-fitting solution that determines the critical ESS parameters (e.g. Din, SS, Dremaining, Dpatent, etc.). Data for this program are loaded manually or from a specially formatted data file. The results of this analysis are monitored and trended using 344SPC and indicate whether or not field reliability will be achieved and to what extent factory TQM goals are being realized.

B.2 Requests for Copies: Government agencies may obtain copies of DOD-HDBK-344, Software Toolkit and Users Manual by completing The Statement of Terms and Conditions provided in Section B.3 below and sending it to RL/ERSR (344 Toolkit), Griffiss AFB NY 13441-5700. In addition, DoD Contractors are required to submit DD Form 2345, Military Critical Technical Data Agreement which can be obtained from the Defense Logistics Service Center, Federal Center, Battle Creek, Michigan 49017-3084.

B.3 Statement of Terms and Conditions

STATEMENT OF TERMS AND CONDITIONS RELEASE OF AIR FORCE OWNED OR DEVELOPED COMPUTER SOFTWARE PACKAGES

Date_____

1. Release of the following US Air Force software package (computer programs, systems descriptions, and documentation) is requested:

2. The requested software package will be used for the following purpose:

Such use is projected to accrue benefit to the Government as follows:

3. I/We will be responsible for assuring that the software package received will not be used for any purpose other than shown in Paragraph 2 above; also, it will not be released to anyone without prior approval of the Air Force. Further, the release of the requested software package will not result in competition with other software packages offered by commercial firms.

4. I/We guarantee that the provided software package, or any modified version thereof, will not be published for profit or in any manner offered for sale to the Government; it will not be sold or given to any other activity or firm, without the prior written approval of the Air Force. If this software is modified or enhanced using Government funds, the Government owns the results, whether the software is the basis of, or incidental to a contract. The Government may not pay a second time for this software or the enhanced or modified version thereof. The package may be used in contract with the Government but no charge may be made for its use.

5. The US Air Force is neither liable nor responsible for maintenance, updating or correcting any errors in the software provided.

6. I/We understand that no material subject to national defense security classification or proprietary rights was intended to be released to us. I/We will report promptly the discovery of any material with such restrictions to the Air Force approving authority. I/We will follow all instructions concerning the use or return of such material in accordance with regulations applying to classified material, adn will make no further study, use, or copy such material subject to security or proprietary rights marking.

7. I/We understand that the software package received is intended for domestic use only. It will not be made available to foreign Governments nor used in any contract with a foreign Government

Signature of Requestor	Signature of Air Force Approving Authority
Name of Requestor	Name/Title of Air Force Approving Authority
Organization/Address	Organization/Location
City, State, and Zip Code	

PART D

REVISED MILITARY HANDBOOK

ENVIRONMENTAL STRESS SCREENING (ESS) OF ELECTRONIC EQUIPMENT

REVISED MILITARY HANDBOOK

ENVIRONMENTAL STRESS SCREENING (ESS) OF ELECTRONIC EQUIPMENT

THIS DOCUMENT SUBMITTED IN ACCORDANCE WITH THE TERMS OF CONTRACT F20602-88-C-0055 BY

LITTON SYSTEMS CANADA LIMITED
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REVISION A

30 APRIL 1991

DEPARTMENT OF DEFENSE

WASHINGTON DC 20301

ENVIRONMENTAL STRESS SCREENING

OF

ELECTRONIC EQUIPMENT

1. This Military Handbook is approved for use by Rome Air Development Center, Department of the Air Force and is available for use by all Departments and Agencies of the Department of Defense.

2. Beneficial comments (recommendation, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: Commander, Rome Air Development Center, ATTN: RBE-2, Griffiss AFB NY 13441-5700, by using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document, or by letter.

Foreword

1. This Handbook provides techniques for planning and evaluating Environmental Stress Screening (ESS) programs. The guidance contained herein departs from other approaches to ESS in that quantitative methods are used to plan and control both the cost and effectiveness of ESS programs. Handbook procedures and methodology were developed under RADC contractual and in-house studies. Contractual efforts were performed by the Hughes Aircraft Company of Fullerton, California, under the direction of Mr. A. E. Saari and Litton Systems Canada Limited of Toronto, Ontario under the direction of Mr. R. A. Pepperall. The Handbook includes the guidance contained in R&M 2000 ESS Policy Letter dated 25 Jun 86.

2. Environmental Stress Screening (ESS) programs, which are applied during the development and production phases, can yield significant improvements in field reliability and reductions in field maintenance costs. Application during development can reap significant savings in test time and costs as a result of eliminating or reducing the number of latent defects prior to qualification tests. The benefits for the manufacturer include: a high degree of visibility as to the sources of reliability problems in the product or process, better control of rework costs, and the opportunity to determine corrective actions which eliminate the sources of reliability problems from the product or process.

3. There are various approaches associated with the application of stress screens. Regardless of the approach used, the fundamental objective of ESS remains the same; i.e., to remove latent defects from the product prior to field delivery. The quantitative methods, contained in this Handbook, extend this objective by focusing on the defects which remain in the product at delivery and their impact on field reliability. The goal of ESS programs thus becomes to reduce the latent defect population, at delivery, to a level which is consistent with the reliability requirements for the product. Reduction of the latent defect population in a production lot of electronic equipment, is accomplished by:

a. Use of ESS to precipitate flaws in the assembled hardware to a detectable level coupled with the use of thorough tests to facilitate their detection and removal.

b. Use of ESS results to isolate defect-failure causes followed by determining appropriate corrective actions. Effective corrective actions eliminate the source (cause) of the defect from the process or product, thereby improving manufacturing process capability.

4. General guidelines and supporting rationale in Section 4 and detailed guidelines in Section 5 provide the user with the procedures needed to plan, monitor and control the screening process so that quantitative goals can be achieved cost effectively. The six detailed procedures of Section 5 are entitled:

Procedure A - Optimizing Screen Selection and Placement
Procedure B - Estimating Defect Density
Procedure C - Estimating Screening Strength
Procedure D - Refining Estimates of Defect Density and Screening Strength
Procedure E - Monitoring and Control
Procedure F - Product Reliability Verification Test (PRVT).

5. It should be noted that is is not possible to eliminate all defects from the hardware through stress screening. The vast majority of parts in the hardware will never fail throughout the life of the product. However, some fraction of the parts contain gross latent defects and tend to fail early and thus dominate the reliability of fielded products during early life. The objective is to remove as many of the gross defects from the hardware as is technically and economically feasible so as to achieve the designed-in or required reliability. The Handbook implements these objectives through use of controls on the latent defects present in the hardware at assembly, the costs to precipitate and remove them, and the assurance needed that latent defects remaining in the hardware at delivery will allow reliability objectives to be achieved.

6. The procedures provided in the Handbook are an important aspect of a manufacturer's TQM program and philosophy. The procedures quantify some elements of customers satisfaction that are measured by cost and reliability and reflect these as factory goals and requirements that are thus meaningfully and directly related to the customers measures of satisfaction. These factory requirements apply to all levels from the procurement of parts and materials from vendors through all factory processes and tests and affect both management and design philosophies. The procedures also provide management and working level groups with quantitative feedback on their performance compared with requirements and goals for continuous improvement. If problem areas or deficiencies are identified the procedures help analyse options for defect control or prevention.

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1. INTRODUCTION

1.1 Purpose. This Handbook provides uniform procedures, methods and techniques for planning, monitoring and controlling the cost effectiveness of ESS programs for electronic equipment. It is intended to support the requirements of MIL-STD-785, Task 301,"Environmental Stress Screening" and to implement Air Force R&M 2000 ESS recommendations and guidelines.

1.2 Application. The Handbook is intended for use by procuring activities and contractors during development and production. It is not intended that the Handbook procedures and techniques be used in a cookbook fashion. Knowledge of the equipment and the manufacturing process is essential for a properly planned and tailored ESS program. The data base needed for a systematic approach to ESS application is not fully developed. Use of the Handbook by Government procuring agencies and equipment manufacturers will foster the development of an improved and broader data base.

1.3 General. A properly applied ESS program can significantly impact the quality and reliability of electronic products delivered to the Government. ESS is interrelated with the requirements set forth in MIL-Q-9858, and MIL-STD-785. Quality Control is a manufacturing function and Reliability Engineering is a design function. Although the Quality and Reliability disciplines are related, in practice, they are conducted as separate programs without common objectives. The Handbook uses the ESS program as a means for integrating Quality Control and Reliability Engineering tasks so as to assure achievement of reliability objectives during manufacture. Supporting software is available from RADC that fully automates the detailed manual procedures contained herein.

1.3.1 What is ESS?. ESS is a process or series of processes in which environmental stimuli, such as rapid thermal cycling and random vibration, are applied to electronic items in order to precipitate latent defects to early failure. An equally important and inseparable aspect of the screening process is the testing which is done as part of the screen, so as to detect and properly identify the defects which have been precipitated to failure. The precipitation and testing process is basically a search for defects. Manufacturing techniques for modern electronic hardware consist of hundreds of individual operations and processes through which defects can be introduced into the product. Many of the defects can be detected without the need for stress screens by use of visual inspections, functional tests and other conventional quality assurance procedures. Such defects are termed errors and are a subset of patent defects. A small percentage of latent defects remain undetected by obvious means and, if not removed in the factory, will eventually manifest as early life failures during product use. The inability to find latent defects by obvious means is a consequence of the increased complexity of modern electronic products and the processes which are used in their manufacture. ESS is the vehicle by which latent defects are accelerated to early failure in the factory. ESS can thus be viewed as an extension of the quality control inspection and testing process.

1.3.2 Organization of the Handbook. The Introduction (Section 1) outlines the purpose of the Handbook and provides general introductory remarks pertaining to the quantitative approach to ESS. Section 2 lists applicable references and Section 3 defines terms and acronyms used. Section 4 contains general guidelines and

provides the rationale and background for the detailed guidelines. Section 5 contains the detailed guidelines which are organized according to the sequence of events to be undertaken by the contractor in planning, monitoring and controlling a screening program. The detailed procedures are entitled:

- Procedure A - Optimizing Screen Selection and Placement
- Procedure B - Estimating Defect Density
- Procedure C - Estimating Screening Strength
- Procedure D - Refining Estimates of Defect Density and Screening Strength
- Procedure E - Monitoring and Control
- Procedure F - Product Reliability Verification Test

Appendix A contains the mathematical relations and model descriptions used in the Handbook. A review of Appendix A will help the interested reader in gaining a quick understanding of the rationale and methodology of the Handbook. Appendix B provides the mathematical foundation for the Product Reliability Verification Test.

Figure 1.1 shows the sequence of application of the various tasks contained in the Handbook and cross-references them to the applicable procedures of the Handbook.

The product development phase is used to experiment with stress screens to refine the estimate of ESS parameters (D_{IN}, SS) and to define and plan a cost effective screening program for the production phase. The incoming latent defect density is estimated (Procedure B) and screens are selectively placed at various assembly levels to develop a plan for achieving quantitative ESS goals cost-effectively (Procedure A). The ESS plan for the development phase should be submitted as part of the Reliability Program Plan (paragraph 4.4.1).

An ESS plan for the production phase is submitted based upon the experimentation and analyses of cost-effectiveness (Para 4.4.1). After the screening program is implemented during production, the fallout from the screens are used to evaluate the screening process and to establish whether ESS program objectives are being achieved (Procedures D and E). Figure 1.2 shows the detailed mathematical model upon which the ESS program is based. The details will be explained as the reader continues.

A Product Reliability Verification test is performed and the results used in conjunction with data from the entire factory ESS program to provide assurance that quantitative objectives have been achieved prior to delivery to the customer (Procedure F). The Quantitative goals for the screening program should be established in accordance with the methods outlined in Procedure A.

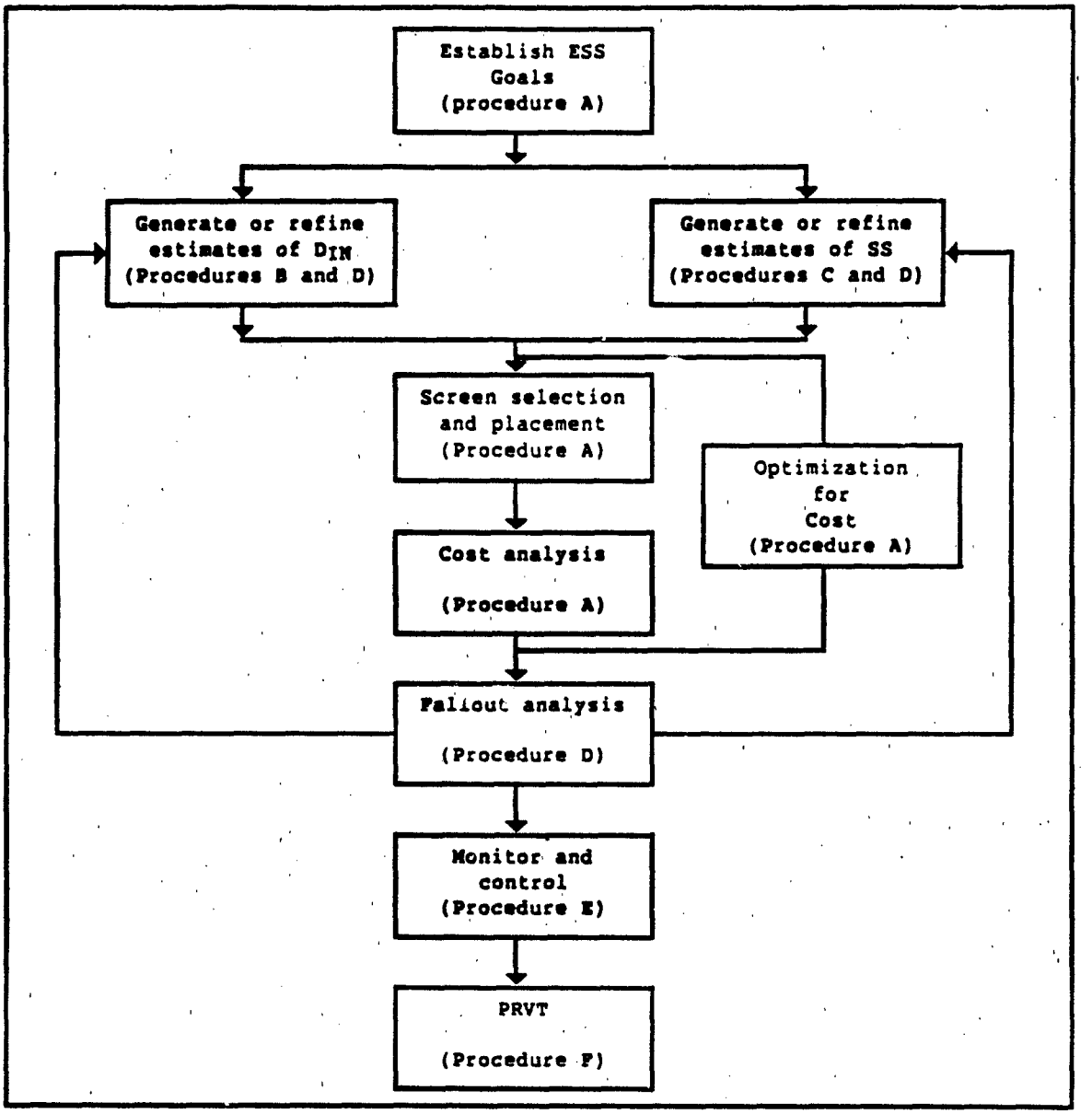
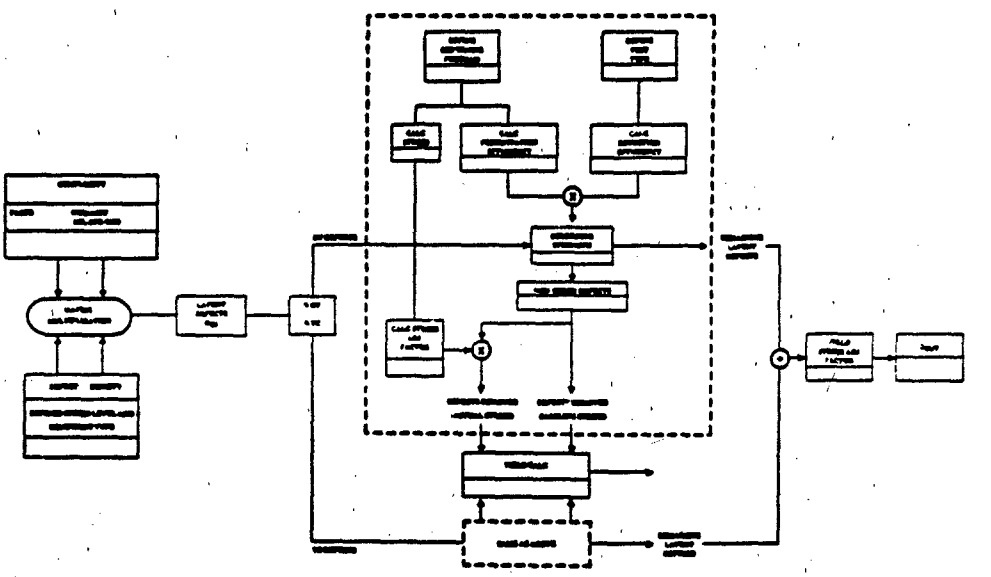


Figure 1.1 Cross Reference of ESS Program Sequence to Handbook Procedures



the mathematical model can be represented by:

$$DREMOVED = DE \times DPAT + DE \times DLAT\ [1 - \exp(-kt)] + DE \times CFR \times t \qquad (A\text{-}9)$$

where DE = detection efficiency

D_{PAT} = patent defects

D_{LAT} = latent defects

k = stress constant

t = stress duration

CFR = constant failure rate

Figure 1.2 Mathamatical Model of an ESS Program

1.3.3 Development and Production Phase Reliability Assurance. ESS is not a substitute for a sound reliability program conducted during the design and development phases. The inherent reliability of the product is driven primarily by the design. However, without a viable reliability assurance program during production, the reliability which is designed into the product can be seriously degraded. An equipment will eventually pass a MIL-STD-781 reliability demonstration test, either during development or on a sample basis during production. A single equipment passing the MIL-STD-781 test does not imply that all other equipments in the production lot have the same reliability. A relatively few latent defects, contained in various equipments in the lot, can significantly reduce the field reliability, especially for equipments with high reliability requirements. A production reliability assurance program which complements the design/development reliability program, is therefore essential to achieving reliability objectives. A properly planned, monitored and controlled stress screening program, structured as part of a production reliability assurance program, is the vehicle through which product reliability in manufacture can be maintained. The identification and prevention of defect causes through ESS and analysis reduces defect densities for production. This information also provides feedback to a lessons-learned data base to avoid similar deficiencies on subsequent designs or changes. The procedures are oriented toward achieving reliability objectives through use of quantitative methods for stress screening and production reliability assurance.

1.3.4 ESS Application and the Quantitative Approach. Historically there have been two basic approaches to the application of stress screens. In one approach, the Government explicitly specifies the screens and screening parameters to be used at various assembly levels. Failure-free periods are sometimes attached to the screens, as acceptance requirements, in order to provide assurance that the product is reasonably free of defects. Another approach is to have the contractor propose a screening program which is tailored to the product and is subject to the approval of the procuring activity. Although the latter approach is preferred, neither approach is adequate since explicit objectives and the relations between the screening program and quantitative reliability requirements are not always defined. Costs are also uncontrolled because some of the screens might be more efficiently performed, at lower assembly levels, where rework costs are lower. In addition, screening levels may far exceed the design limits of the product and result in damage to the equipment.

There are several unknowns associated with the application of stress screens. How effective are the screens? What is considered acceptable or unacceptable fallout from a screen? How does the quantity of defects remaining in the equipment after delivery to the customer impact field reliability? The aforementioned ESS approaches do not fully address these questions. For example, if the screen fallout is "low", it is not known whether the equipment is "good" (i.e., defect-free) or whether the screen is not effective. On the other hand, if the fallout is "high", it is not known whether the incoming defect levels are inordinately high or whether the screen might be causing non-defectives to fail.

Screens and tests are not perfect. At each stage of manufacture where screens and tests might be applied, from device level to the final system level, escapes to the next assembly stage occur, and new opportunities for introducing defects are

created. The number of latent defects which remain in the product at delivery and their impact on field reliability, however, is the primary concern.

1.3.4.1 The Quantitative Approach. The use of a quantitative approach to stress screening requires that the initial part latent defect levels, the defect level introduced during manufacture of the product, the effectiveness of the screens, and reasonably acceptable values for the number of latent defects which remain and escape into the field be addressed. Figures 1.3 and 1.4 illustrate the quantitative aspects of stress screening.

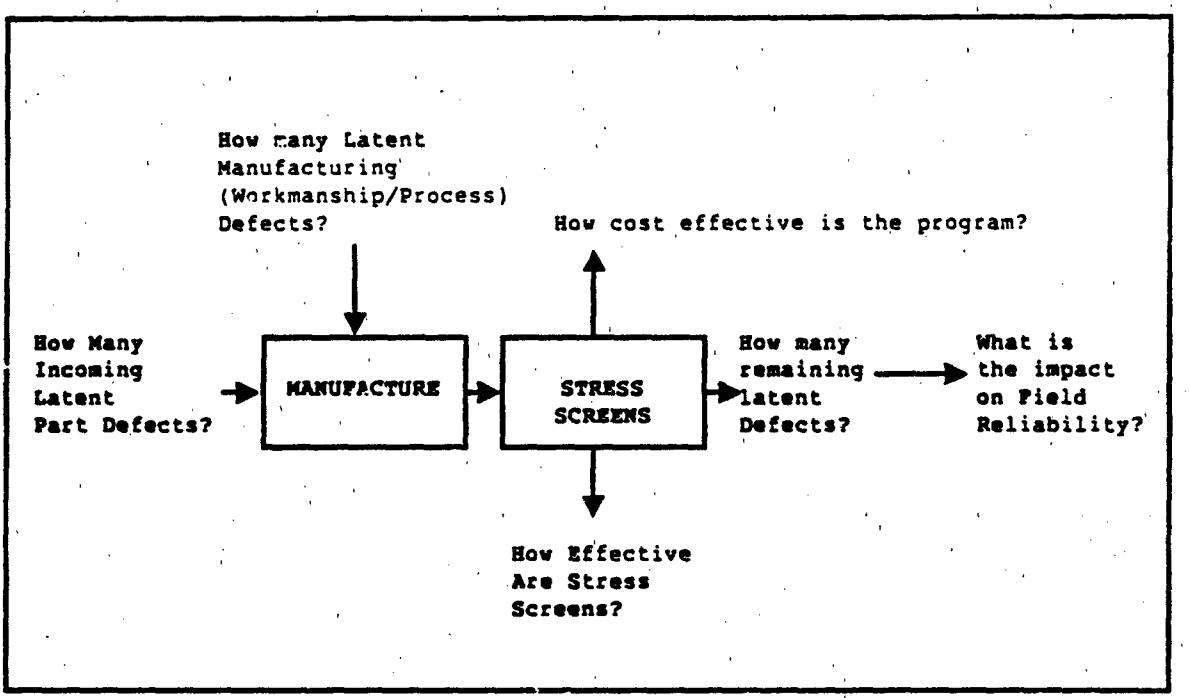


Figure 1.3 The Quantitative Problem

When a quantitative approach to stress screening is used, the key variables of interest are the average number of defects per product which enter the screen (D_{in} comprised of latent defects (Dl)and patent defects (Dp and E)), the screen strength (SS) which is the product of Precipitation Efficiency (PE) and Detection Efficiency (DE) and the average number of defects per product which escape the screen/test ($D_{REMAINING}$). Figure 1.4 shows the relationships between these stress screening variables.

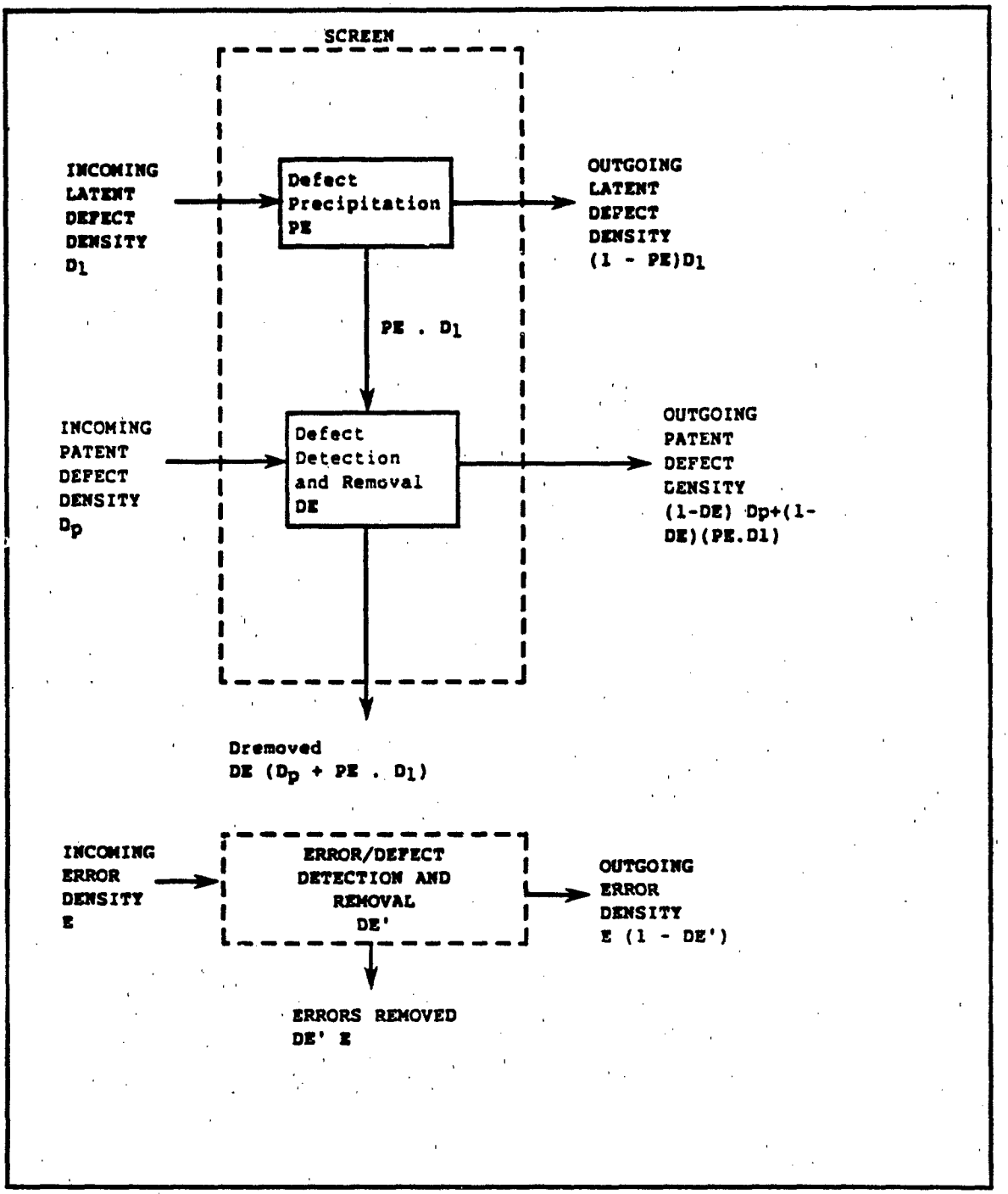


Figure 1.4 Stress Screening and Variable Relationships

The number of defects remaining in the production lot at delivery is a function of three key factors:

a. The quantity of design, part and manufacturing (workmanship and process) defects which initially reside in the hardware prior to assembly level screening.

b. the capability of the environmental stress to precipitate flaws in assemblies to a detectable level.

c. The thoroughness of the testing which is done, either during or after the screen, to assure detection of the defects precipitated to failure by the screens and the ability to fault isolate and remove the defect without introducing new flaws.

None of the three factors which impact the reliability of delivered products is known with certainty. Without a basic knowledge of their quantitative value, however, effective screening programs cannot be properly planned and controlled. The procedures in the handbook are directed to obtaining both preliminary planning and measured estimates of the three factors in order to plan, monitor and control the screening process. Experience data gathered from previous screening programs, screening experiments conducted during the development phase and use of the handbook procedures provides the methodology and information needed to plan and conduct effective screening programs.

Once a screening program is implemented during production, the results must be monitored and appropriate changes made in the screening regimen to assure that goals on remaining defects are achieved. The basic mechanism for assuring control is to compare the screening results with established goals so as to determine the need for corrective actions. For example, corrective actions might be accomplished by increasing precipitation or detection efficiencies so that more defects can be precipitated and detected, or by reducing incoming defect quantities through improved process controls. Changes which reduce or eliminate screening at some levels of assembly can also be taken to reduce costs, when it is found that the screens are ineffective or unnecessary.

1.3.5 Benefits of a Quantitative Approach. A quantitative approach to stress screening enables the establishment of explicit quantitative objectives and provides a basis for planning, monitoring and controlling the screening process to meet those objectives. A quantitative approach also facilitates Government and contractor communication on the status of the screening process and on the progress being made toward achieving objectives. Coupled with a good Failure Reporting Analysis and Corrective Action System (FRACAS), the quantitative approach also provides a more focused emphasis on the sources of latent reliability problems in the product or process as well as better control of costs.

1.3.6 Process Capability and Defect Density. The use of a quantitative approach to stress screening requires addressing the capability of the manufacturing process to produce products which are reasonably free of defects. Defects are introduced into a lot of manufactured products through repeated assembly, handling and testing operations. The average number of defects per product (defect density) varies as a function of the degree of control which is exercised over the manufacturing process

and the process capability. The ESS program addresses the questions: What is the process capability?, What must the process capability be in order to meet quantitative reliability objectives? What improvements and changes are required to achieve the reliability objectives at optimum cost?

2. REFERENCED DOCUMENTS

The documents cited in this section are for guidance and information.

2.1 Government Documents.

SPECIFICATIONS

MIL-Q-9858	Quality Program Requirements

STANDARDS

MIL-STD-721	Definition of Terms for Reliability and Maintainability
MIL-STD-781	Reliability Design Qualification and Production Acceptance Tests: Exponential Distribution
MIL-STD-785	Reliability Program For Systems and Equipment Development and Production
MIL-STD-883	Test Methods and Procedures for Microelectronics
MIL-STD-2000	Standard Requirements for Soldered Electrical and Electronic Assemblies

HANDBOOKS

MIL-HDBK-217	Reliability Prediction of Electronic Equipment

PUBLICATIONS

Air Force

AFWAL-TR-80-3086 Aug 80	Environmental Burn-In Effectiveness
RADC-TR-82-87 May 82 (AD-A118261)	Stress Screening of Electronic Hardware
RADC-TR-86-138	RADC Guide to Environmental Stress Screening
RADC-TR-86-149	Environmental Stress Screening

Navy

NAVMAT P-9492	Navy Manufacturing Screening Program

(Copies of specifications, standards, handbooks, drawings, and publications required by contractors in connection with specific acquisition functions should be obtained from the contracting activity or as directed by the contracting officer.)

2.2 Nongovernment Documents.

Institute of Environmental Sciences (IES)

Environmental Stress Screening Guidelines, 1981

Environmental Stress Screening Guidelines for Assemblies, Sep 84

(Application for copies should be addressed to the Institute of Environmental Sciences, 940 East Northwest Highway, Mt Prospect IL 60056-3444)

Electronic Industries Association (EIA)

Interim Standard No. 18 Lot Acceptance Procedure for Verifying Compliance with the Specified Quality Level (SQL) in PPM

(Application for copies should be addressed to the Electronic Industries Association, 2001 Eye Street, NW, Washington DC 20006 5009)

2.2.1 Other Nongovernment Documents.

Fertig, K.W., Murthy, V.K., "Models for Reliability Growth During Burn-In", Proceedings of the 1978 Annual R&M Symposium, pp 504-509.

Bateson. J.T., "Board Test Strategies - Production Testing in the Factory of the Future", Test and Measurement World, pp. 118-129, Dec 84.

Kube, F., Hirschberger, G., "An Investigation to Determine Effective Equipment Acceptance Test Methods", Grumman Aerospace Corporation, Report No., ADR 14-04-73, Apr 73

Brownlee, K.A. (1960), Statistical Theory and Methodology in Science and Engineering, New York, John Wiley and Sons

Crandall, Random Vibration, John Wiley and Son

Engelmaier, Effects of Power Cycling in LCC, Bell Laboratories N.J.

(Nongovernment documents are generally available for reference from libraries. They are also distributed among nongovernment standards bodies and using Federal agencies.)

3. DEFINITIONS AND ACRONYMS

3.1 Definitions. Definitions applicable to this Handbook are:

Assembly/Module	A number of parts joined together to perform a specific function and capable of disassembly, for example a printed circuit assembly. An assembly of parts designed to function in conjunction with similar or different modules when assembled into a unit. (eg. power supply module, core memory module.)
Baseline Stress	Factory ESS stress levels consistent with R&M 2000 guidelines i.e., 6 Grms, 2°C/min. Measured at Unit Under Test
Chamber	Cabinet in which hardware is placed in order to apply stress to it.
Defect Density	Average number of latent defects per item. Symbols used: D_{IN}, D_{OUT}, $D_{REMAINING}$ and D_O for incoming, outgoing, remaining and observed defect density, respectively.
Detectable Failure	A failure that can be detected with 100% detection efficiency.
Detection Efficiency	A measure of the capability of detecting a patent defect. Symbol is DE.
Error	Class of patent defect resulting from assembly and/or test correlation errors. Errors do not require environmental stress for precipitation or detection.
Escapes	The incoming defect density which is not detected by a screen and test and which is passed on to the next level.
Failure-Free Period	A contiguous period of time during which an item is to operate without the occurrence of a failure while under environmental stress.
Failure Rate	The total number of failures within an item population, divided by the total number of life units expended by that population during a particular measurement interval under stated conditions. Symbol is λ. A reliability measure related to MTBF.
Fallout	Failures observed during, or immediately after, and attributed to stress screens. Symbol is F. Sometimes used to mean defects removed, symbol $D_{REMOVED}$.

Fault Coverage	In a given piece of equipment, the ratio of faults which are detectable to faults present.
Latent Defect	An inherent or induced weakness, not detectable by ordinary means, which will either be precipitated to early failure under environmental stress screening conditions or eventually fail in the intended use environment.
Part	Any identifiable item within the product which can be removed or repaired (e.g., discrete semiconductor, resistor, IC, solder joint, connector).
Part Fraction Defective	The number of defective parts contained in a part population divided by the total number of parts in the population expressed in PPM. See also defect density.
Patent Defect	An inherent or induced weakness which can be detected by inspection, functional test, or other defined means. Symbol is D_{pat}. In this procedure, D_{pat} refers to precipitated latent defect. See also error.
Precipitation (of Defects)	The process of transforming a latent defect into a patent defect through the application of stress screens.
Precipitation Efficiency	A measure of the capability of a screen to precipitate latent defects to failure. Symbol is PE.
Production Lot	A group of items manufactured under essentially the same conditions and processes.
Product Reliability Verification Test	A test to provide confidence that field reliability will be achieved.
Screenable Latent Defect	A latent defect that when removed, results in a lower equipment failure rate.
Screen Parameters	Parameters in screening strength equations which relate to screening strength, (e.g., vibration G-levels, temperature rate of change and time duration).
Screening Regimen	A combination of stress screens applied to an equipment, identified in the order of application (i.e., assembly, unit and system screens).
Screening Strength	The probability that a specific screen will precipitate a latent defect to failure and then detect the resultant patent defect, given that a

	latent defect susceptible to the screen is present. It is the product of precipitation efficiency and detection efficiency. Symbol is SS.
Selection and Placement	The process of systematically selecting the most effective stress screens and placing them at the appropriate levels of assembly.
Stress Adjustment Factor	The ratio of the incoming defect density at the anticipated field stress level to the incoming defect density at the base line stress level.
Stress Screening	The process of applying mechanical, electrical and/or thermal stresses to an equipment item for the purpose of precipitating latent part and workmanship defects to early failure.
System/Equipment	A group of units interconnected or assembled to perform some overall electronic function (e.g., electronic flight control system, communications system).
Thermal Survey	The measurement of thermal response characteristics at points of interest within an equipment when temperature extremes are applied to the equipment.
Unit	A self-contained collection of parts and/or assemblies within one package performing a specific function or group of functions, and removable as a single package from an operating system (i.e., autopilot computer, vhf communications, transmitter).
Vibration Survey	The measurement of vibration response characteristics at points of interest within an equipment when vibration excitation is applied to the equipment.
Yield	The probability that an equipment will pass a screen or test without failure.

3.2 Acronyms/Abbreviations

3.2.1 Acronyms use in procedure B of section 5

Abbreviation	Description
AIC	Airborne Inhabited Cargo
AIT	Airborne Inhabited Trainer
AIB	Airborne Inhabited Bomber
AIA	Airborne Inhabited Attack
AIF	Airborne Inhabited Fighter
AUC	Airborne Uninhabited Cargo
AUT	Airborne Uninhabited Trainer
AUB	Airborne Uninhabited Bomber
AUA	Airborne Uninhabited Attack

AUF	Airborne Uninhabited Fighter
ARW	Airborne Rotary Wing
CL	Cannon Launch
GB	Ground Benign
GF	Ground Fixed
GM	Ground Mobile
ML	Missile Launch
MFF	Missile Free Flight
MFA	Airbreathing Missile Flight
MP	Manpack
NS	Naval Sheltered
NU	Naval Unsheltered
NUU	Naval Undersea Unsheltered
NSB	Naval Submarine
NH	Naval Hydrofoil
SF	Space Flight
USL	Undersea Launch

3.2.2 Other Acronyms

Abbreviation	Description
AOQL	Average Outgoing Quality Limit
ATP	Acceptance Test Procedure
BIT	Built In Test
CND	Cannot Duplicate
CDE	Chance Defective Exponential
DE	Detection Efficiency
ESD/EOS	Electrostatic Discharge/Electrical Overstress
ESS	Environmental Stress Screening
FRACAS	Failure Reporting and Corrective Action System
FL	Fault Location
FMEA	Failure Mode & Effect Analysis
FBT	Functional Board Tester
IC	Integrated Circuit
ICT	In Circuit Tester
ICA	In Circuit Analyzer
LBS	Loaded Board Shorts
LRU	Line Replaceable Unit
LSI	Large Scale Integration
LTPD	Lot Tolerance Percent Defective
MTBF	Mean Time Between Failures
MLE	Maximum Likelihood Estimate
MSI	Medium Scale Integration
NFF	No Fault Found
OEM	Original Equipment Manufacturer
PE	Precipitation Efficiency
PEP	Production Engineering Phase
PCB	Printed Circuit Board
PPM	Parts Per Million
PRVT	Product Reliability Verification Test
PWA	Printed Wiring Assembly
PM	Performance Monitoring

RTOK	Retest OK
SAF	Stress Adjustment Factor
SRU	Shop Replaceable Unit
SQL	Specified Quality Level
SPC	Statistical Process Control
TAAF	Test Analyze & Fix
TQM	Total Quality Management

4. GENERAL GUIDELINES

4.1 Contractual Aspects of ESS. ESS must remain an adaptive process so that the screening regimen can be changed to improve cost-effectiveness. Contract provisions for ESS programs should have flexibility to effect necessary modifications of stress screens. During the initial stages of production more severe stress screens may be required. As the product and process mature, the screens may require adjustment such as by reducing the number of temperature cycles, the number of axes of vibration or by eliminating unnecessary screens. In early production, a number of unknowns preclude adoption of optimum stress screening. Some of the more significant unknowns are:

a. Residual design deficiencies
b. Manufacturing planning errors
c. Worker training
d. New suppliers
e. Latent defects in new part lots
f. New process capability
g. Precipitation Efficiency
h. Detection Efficiency

The stress screening program, even if carefully planned, may produce unexpected results which should be addressed through modification of the screens. The principle of adaptive screening is to adjust the screens on the basis of observed screening results so that the screens are always most cost effective while meeting ESS program goals. Contract terms should be flexible enough to permit modification of screens or screen parameters when such modification can be shown to be beneficial.

In long term production the quantity and distribution of latent defects changes with time and therefore contract terms should contain provisions for periodically reassessing the individual screens and the overall screening program. The overriding criterion for change should be the most cost effective achievement of objectives. Contracting arrangements should be made which permit such changes without having to resort to extensive renegotiation.

4.2 Relation of ESS to MIL-STD-785 Reliability Program Tasks. Planning an ESS program for the production phase is interrelated with many of the MIL-STD-785 reliability program tasks which are required to be performed during development and production. Every effort should be made to integrate the knowledge gained from MIL-STD-785 tasks into the planning of an ESS program for production. MIL-STD-785 reliability program tasks which have a particular bearing on ESS planning include Reliability Prediction (Task 203), Reliability Allocation (Task 202), Qualification Tests (Task 303), Parts Program (Task 207), Failure Reporting Analysis and Corrective Action System (Task 104), Failure Modes, Effects and Criticality Analysis (Task 204), Reliability Growth Testing (Task 302), and of course, ESS (Task 301). Proper screen selection and placement is highly dependent on the reliability and stress design characteristics of the equipment. Information derived from reliability program tasks such as predicted and demonstrated failure rates, quality level of parts, number and type of nonstandard and MIL-parts, number

and type of interconnections, design capability, field stress environments, and critical items should be used in structuring an ESS program for production.

4.3 Subcontractor and Supplier Stress Screening. Items which are furnished by subcontractors or other equipment suppliers may require stress screening. There are several distinct advantages for the subcontractor or supplier to perform the stress screening rather than the prime contractor.

a. Subcontractor/supplier concern for yield can be translated to profits which may force process improvements to minimize latent defects.

b. Screening at receiving inspection/test, by the prime contractor, may involve returning defective items to the subcontractor/supplier and result in shortages and schedule slippages. Performing the additional screen can introduce latent defects due to handling eg. mechanical and ESD damage and electrical over stress.

c. Special stress screening facilities and test equipment do not have to be purchased, supported and operated by the prime contractor.

The procedures and methodology contained in the Handbook can be imposed on the subcontractor/supplier. To assure that the subcontractor/supplier is able to perform the tasks required by the Handbook the intent must be made known prior to production. In this manner, the subcontractor/supplier can prepare a screening plan, acquire the necessary capability or arrange for an external laboratory to perform the screening.

4.3.1 Screening of Spares. Spares should be subjected to a screening regimen equivalent to that used for the production hardware. Spares are either manufactured on the same production line or are produced separately to the same specifications as the production hardware. The spares are most often an LRU or SRU and consequently may not receive the exposure to additional screening at higher assembly levels that non-spare items might receive. Quantitative ESS goals for the system should be allocated down to the spare item. The procedures of Section 5 can be used to ensure that defect density for the spares does not exceed allocated goals. A costly and less desirable alternative would be to screen and test all spares in a mock-up configuration for the system.

4.4 Planning a Stress Screening Program. Planning a stress screening program must begin early in the design phase to ensure that the equipment can withstand the necessary ESS stress levels. The success of a stress screening program is strongly dependent on knowledge of the product and the processes to be used in manufacture. The following must be kept in mind when planning a stress screening program using quantitative methods:

a. The defects which can potentially reside in the product and the effectiveness of screens in precipitating the defects to failure (and then detecting them) are not known with certainty. By comparing planned estimates for defect fallout with actual screen

fallout, the screening and manufacturing process can be adapted to achieve desired goals.

b. Experience data on equipment similar in composition, construction and degree of maturity, can provide very useful data for planning purposes. Information derived from the following sources should be used in planning an ESS program for production:.

(1) Identification of hardware items (parts, assemblies) which have exhibited a high incidence of latent defectives on other programs.

(2) Identification of suppliers/vendors whose products have indicated high defect levels.

(3) Qualification test results.

(4) Supplier acceptance test results.

(5) Part receiving inspection, test and screening results.

(6) Screening and test records for previous programs.

(7) Reliability growth test results.

(8) Field failure data.

c. A viable screening program must be dynamic, i.e. the screening process must be continuously monitored to ensure that it is both technically and cost effective. Changes to the screening process should be made, as necessary, based on analysis of screening fallout data and failure analysis so that quantitative screening objectives can be achieved.

d. The basic questions which must be addressed in planning a stress screening program are:

(1) What are the quantitative objectives of the programs?

(2) What are the stress screens to be used and at what level of assembly should the screens be placed to achieve the desired objectives?

(3) What are the costs associated with each of the possible alternative screening sequences and how can the screening program be made cost effective?

(4) How will one know if the screening program is proceeding according to plan? What assurances can be provided that program objectives have been achieved?

(5) What corrective actions must be taken to achieve desired screening program goals if the screening fallout data indicate significant departures from the planned program?

e. An ESS program for the production phase should include the following major tasks:

(1) Preparation of ESS Plan
(2) Establish Objectives/Goals
(3) Obtain Planning Estimates of Defect Density
(4) Selection and Placement of Screens to optimize cost

A discussion of each of these major tasks which includes background, rationale and general guidelines for use of the detailed procedures is contained in 4.4.1 through 4.4.5.

4.4.1 Preparation of ESS Plans. The contractor should prepare ESS plans for both the development and production phases. The purpose of the development phase plan is to describe the proposed application of ESS during development and production and to validate and refine the estimated values of D_{IN} and SS. Use of the procedures contained in the Handbook in conjunction with stress screen experimentation on pre-production prototype equipment can provide invaluable data for planning. Estimates of the type and quantity of defects likely to be present in the hardware can be evaluated against experimental data. Screens can be designed, based upon engineering evaluation, which provide the desired stress stimulation for suspected defect sites in the hardware. Test specifications can also be evaluated to ensure that possible failure modes, arising from various defect types and sources, can be detected by the tests performed either during or following the screens. Integration of the results from the MIL-STD-785 reliability program tasks can also be effectively accomplished. Early fallout from screens provides the maximum amount of information on likely defect sources and process capability. Corrective actions taken as a result of screen experimentation during development can aid significantly in stabilizing the process for production. The development phase and production phase ESS plans should be submitted for approval by the procuring activity prior to production.

4.4.1.1 Development Phase Plan. The development phase plan should include the following:

a. Identification of the reliability requirements for the product and the quantitative goals for the ESS program.

b. Identification of the equipment to be screened and the respective production quantities.

c. Description of the initial screens which will be applied and the screening experiments which will be conducted.

d. Description of the data collection and analysis program which will be used.

e. Description of subcontractor and supplier stress screening to be performed.

f. Results of preliminary use of the handbook procedures.

g. Identification of the organization elements that will be responsible for ESS planning and experimentation, and the conduct of development phase screening activity.

4.4.1.2 Production Phase Plan. The production phase plan shall include the following:

a. Quantitative objectives of the ESS program.

b. Detailed breakdown to the assembly level of the equipment which will be screened.

c. Description of the screens which will be applied, including screen parameters and exposure time.

d. Description of the results in applying Procedures A through E of Section 5 including the rationale for achieving quantitative objectives in a cost effective manner.

e. Description of the FRACAS and the analyses procedures which will be used to evaluate and control the screening process.

f. Description of the PRVT to be performed to verify achievement of objectives.

g. Identification of the organizational elements responsible for conducting and evaluating the effectiveness of the production ESS program.

4.4.2 Establishing Objectives/Goals. Expressed quantitatively, the objective of a stress screening program is to reduce the incoming latent defect density in a production lot of equipment to an acceptable remaining latent defect density in a cost effective manner. Equipments having high reliability requirements will have more stringent goals on remaining defect density. Methods for determining goals on remaining defect density are discussed in Appendix A. The remaining latent and patent defects determine the field reliability according to the following expression:

$$\text{Average Failure Rate in Field} = \frac{\text{Total failures in time T}}{T} = \text{MTBF}$$

= summation of (Dpat + Dlat.SAF.[1-exp(-kT)]+ CFR.T)/T for all environments

where: Dpat = remaining patent defects

Dlat = remaining latent defects
SAF = Stress Adjustment Factor
k = precipitation stress constant

Note that the DE terms are absent since the field DE is 1 by definition.

Using this relationship, the required field failure rate can be used to determine the requirements for remaining defect density and consequently used to establish goals and requirements for all integration and test levels from incoming defect densities for parts through to final equipment testing.

An example relating various values of Dremaining to the field MTBF is shown in Table 4.1 for an assumed field precipitation rate k=1/1000 Hr.

Table 4.1 Remaining Defect Density Goals (DR)

Failure Rate (Failures/Hours)	MTBF	$D_{REMAINING}$ (At Field Stress)
0.009516	105	10
0.000951	1051	1
0.000475	2102	0.5
0.000190	5254	0.2
0.000095	10508	0.1
0.000047	21017	0.05
0.000019	52542	0.02
0.000009	105083	0.01
0.000000	1050833	0.001

4.4.3 Obtaining Planning Estimates of Defect Density. The design of a stress screening program requires knowledge of the quantity and type of latent defects which are likely to reside in the hardware prior to assembly level screening. The defect density tables contained in Procedure B of Section 5 are used to obtain planning estimates of defect density. Values in the tables are based upon studies of historical defect data from the factory and field for several part types. Extrapolations to other part types and field environments were made based upon correlations to MIL-HDBK-217 quality level and field environment factors. Study results and methodology are contained in RADC-TR-86-149. Procedure D provides the methodology that allows the user to refine these estimates based on experience data.

4.4.3.1 Latent vs Patent Defects. A common understanding of the nature of the defects which the screening program should be designed to precipitate is essential for proper planning. The factors which impact incoming defect density and the rationale for the procedures used in obtaining planning estimates of defect density should also be understood.

For ESS purposes defects can be categorized into two types,latent and patent. A latent defect is characterized as an inherent or induced weakness or flaw with some residual strength and will manifest itself as a failure at some time in the future

when exposed to stress (electrical,mechanical, or chemical). Latent defects can not be detected until precipitated as a patent defect. For simplicity,a defect with no residual strength but requiring stress concurrent with testing to be detectable can also be considered to be a latent defect until it is detected. Some examples of latent defects are:

(1) Parts
- (a) Partial damage through electrical overstress or electrostatic discharge
- (b) Partial physical damage during handling
- (c) Material or process induced hidden flaws
- (d) Damage inflicted during soldering operations (excessive heat)

(2) Interconnections
- (a) Cold solder joint
- (b) Inadequate/excessive solder
- (c) Broken wire strands
- (d) Insulation damage
- (e) Loose screw termination
- (f) Improper crimp
- (g) Unseated connector contact
- (h) Cracked etch
- (i) Poor contact termination
- (j) Inadequate wire stress relief

A patent defect is a defect that is detectable in its present form and has two subcategories, error and precipitated latent. An error is a defect caused by workmanship or test correlation. Errors are preventable and should not occur, whereas patent defects due to precipitated latent defects are only preventable to the limits of the state of the art in equipment and technology. Errors can be readily monitored using conventional SPC techniques and can be removed by simple testing or inspection without the need for ESS or environmental stress.

Errors are introduced into the product during fabrication, and assembly, and pass through various assembly stages until they are detected by a test or inspection of sufficient thoroughness and subsequently eliminated from the product. When good quality control test and inspection procedures are applied, all but the most subtle errors should be detected and eliminated prior to shipment. Some examples of errors are:

(1) Parts
- (a) Broken or damaged in handling
- (b) Wrong part installed
- (c) Correct part installed incorrectly
- (d) Missing parts
- (e) Electrical test correlation and tolerancing

(2) Interconnections
- (a) Incorrect wire termination
- (b) Open wire due to handling damage

(c) Wire short to ground due to misrouting or insulation damage
(d) Missing wire
(e) Open etch on printed wiring board
(f) Open plated - through hole
(g) Shorted etch
(h) Solder bridge
(i) Loose wire strand

A precipitated latent defect is a latent flaw that has been transformed into a patent defect by exposure to stress over time. Since detection efficiency is not 100%, some precipitated latent flaws, and errors, will escape to the field as undetected defects. It is thus important to address the aspects of precipitation and detection separately, and also to distinguish and separately monitor errors and precipitated latent flaws. For simplicity the Handbook shall use the term patent defect to define a precipitated latent defect.

4.4.3.2 Categories of Defects. The majority of parts and connections within an electronic equipment will never fail over the product's lifetime and are thus "good". The failures which occur during product life are traceable to design or externally induced causes, or to latent defects which were introduced into the product during manufacture. Such defects, if not eliminated from the product in the factory, will result in premature or early-life failures in the field. Not all latent defects however, are screenable i.e., capable of being eliminated from the equipment in the factory by use of stress screens. It is only those latent defects, whose failure threshold can be accelerated by the stresses imposed by the screens, which are screenable. It is the screenable early life failure which the stress screening program must be designed to remove. Figure 4.1 illustrates the categories of defects and their relationship to product life failures.

4.4.3.2.1 Screenable Latent Defects and the Field Stress Environment. The notion of screenable latent defects must be further examined to fully understand the rationale used for the procedures contained in the handbook. The population of latent defects within newly manufactured electronic items can be viewed as a continuum which ranges from minor defects of small size to major defects of large size.

However, it is important to note a somewhat controversial point, i.e., given the same manufacturing process, the number of latent defects which may reside in the hardware will differ, depending upon the operating environment and stress levels to which the equipment will be exposed. The stress/time to which a latent defect is exposed will determine its failure threshold and time-to-failure. The probability of a latent defect's failure threshold being exceeded is much higher in a harsh environment than in a more benign environment.

Obtaining an initial estimate of defect density for an equipment must take into consideration the field operating environment to which the equipment will be exposed during product life.

Since the operating environmental stress levels are different and less than the factory ESS levels, the field defect density estimate is not directly applicable to the factory ESS program. Further, the producer must design, assess, and monitor

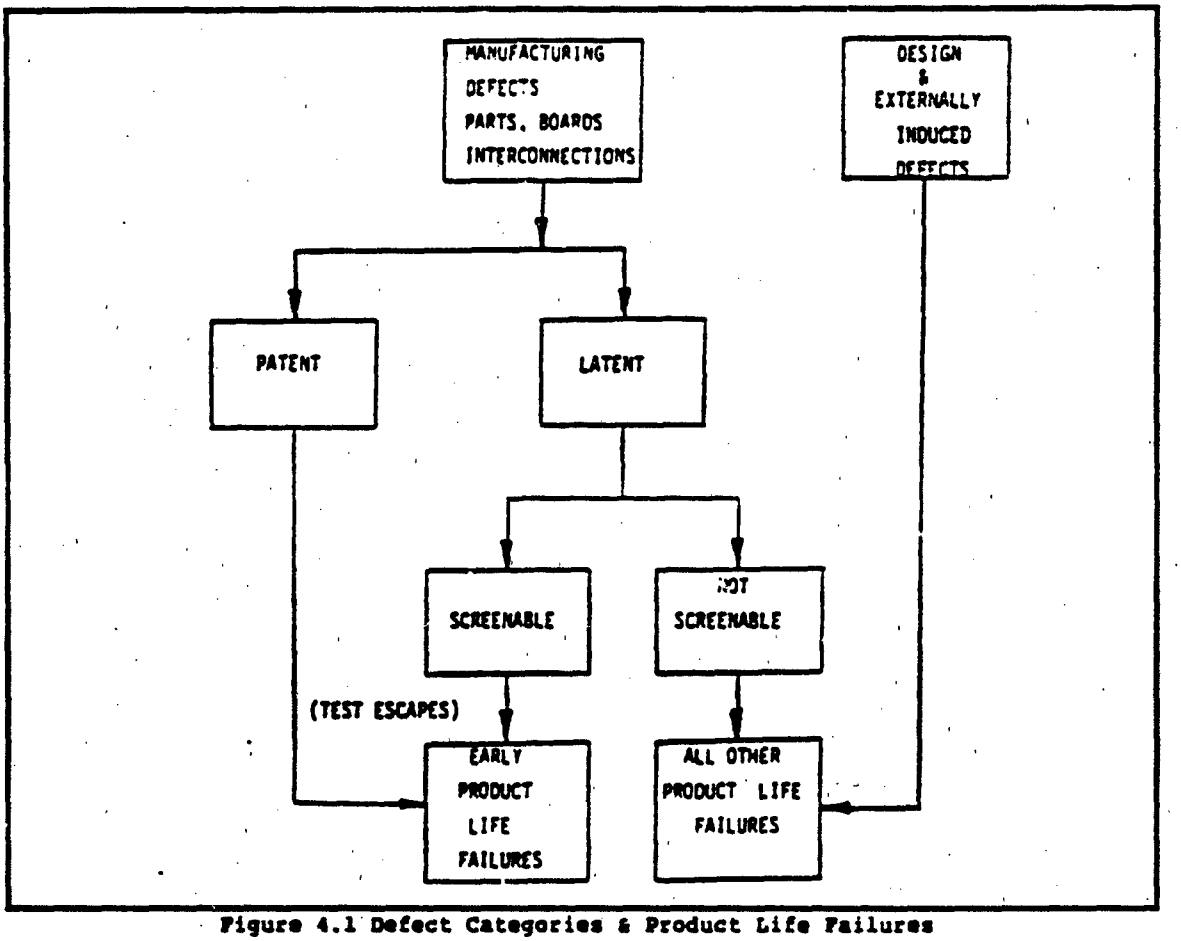


Figure 4.1 Defect Categories & Product Life Failures

the ESS program based upon analysis of factory fallout data and causes. Some method must thus be provided to relate defect density in the field to the factory defect density. This is accomplished by including a stress adjustment factor (SAF) in the model, where

$$\text{STRESS ADJUSTMENT FACTOR} = \frac{\text{DEFECT DENSITY (FIELD STRESS)}}{\text{DEFECT DENSITY (FACTORY STRESS)}}$$

The application and measurement of the SAF is described in Procedures B and E respectively of section 5.

4.4.3.3 Factors Which Impact Defect Density. The quantity and type of defects which are introduced into a product are dependent upon several factors. The first six factors, listed below, are related to product or program characteristics for which the manufacturing function within a company has little control. The last two factors are related to the manufacturing process for which the manufacturing function has direct control.

a. Complexity - The quantity and type of parts and interconnections used in the product affects defect density. Increased complexity creates more opportunities for defects.

b. Part Quality Level/Grade - The quality levels of parts are established by MIL-STD part screening requirements. The number of defects which remain in a lot of screened parts is determined by the type and extent of screening and testing to which the parts are subjected under MIL-STD screening requirements.

c. Stress Environment - The stress conditions to which the equipment will be exposed will affect the proportion of defects which should be screened from the product. A defect may be precipitated to early failure in a harsh field operating environment, but may survive product life in a benign field environment.

d. Process Maturity - New production requires time to identify and correct planning and process problems, train personnel and to establish vendor and process controls. Maturity is dependent on volume and time. Low production volume over a long period would have a low maturity rate and will thus impact defect density.

e. Packaging Density - Electronic assemblies with high part and wiring density are more susceptible to process, workmanship and temperature induced defects due to smaller error margins, increased rework difficulty and thermal control problems.

f. Concurrent Engineering - Proper design analysis and assessment and application of Concurrent Engineering principles during the design stage will tend to ensure a reliable and producible product and thus reduce the latent (and error) defect densities. Durability analyses will also ensure that the design can withstand the stresses of ESS.

The following factors are under the direct control of the manufacturing function. The degree of control exercised will determine defect density. Screen fallout data provide the necessary input for determining out-of-control conditions.

g. Manufacturing Process Controls - Good process controls will tend to reduce the number of defects which are introduced into the product. The criteria by which processes are considered to be in or out of control should be established by reliability requirements and monitored using the fallout from the screening process.

h. Workmanship Quality Standards - Stringent and properly enforced workmanship quality standards will enhance the reliability of the product through reduced introduction of

workmanship defects into the product. The levels to which quality standards should be established and monitored must also be dictated by reliability requirements and made visible by the screening process.

4.4.3.3.1 Part vs Assembly Defect Density. The part defect density can have a significant impact on the assembly defect density depending upon the number of parts contained in the assembly. The Poisson approximation is used in Figure 4.2 to illustrate the expected assembly defect density as a function of the remaining part defect density and the number of parts per assembly. As can be noted relatively small values of part defect density result in large values of assembly

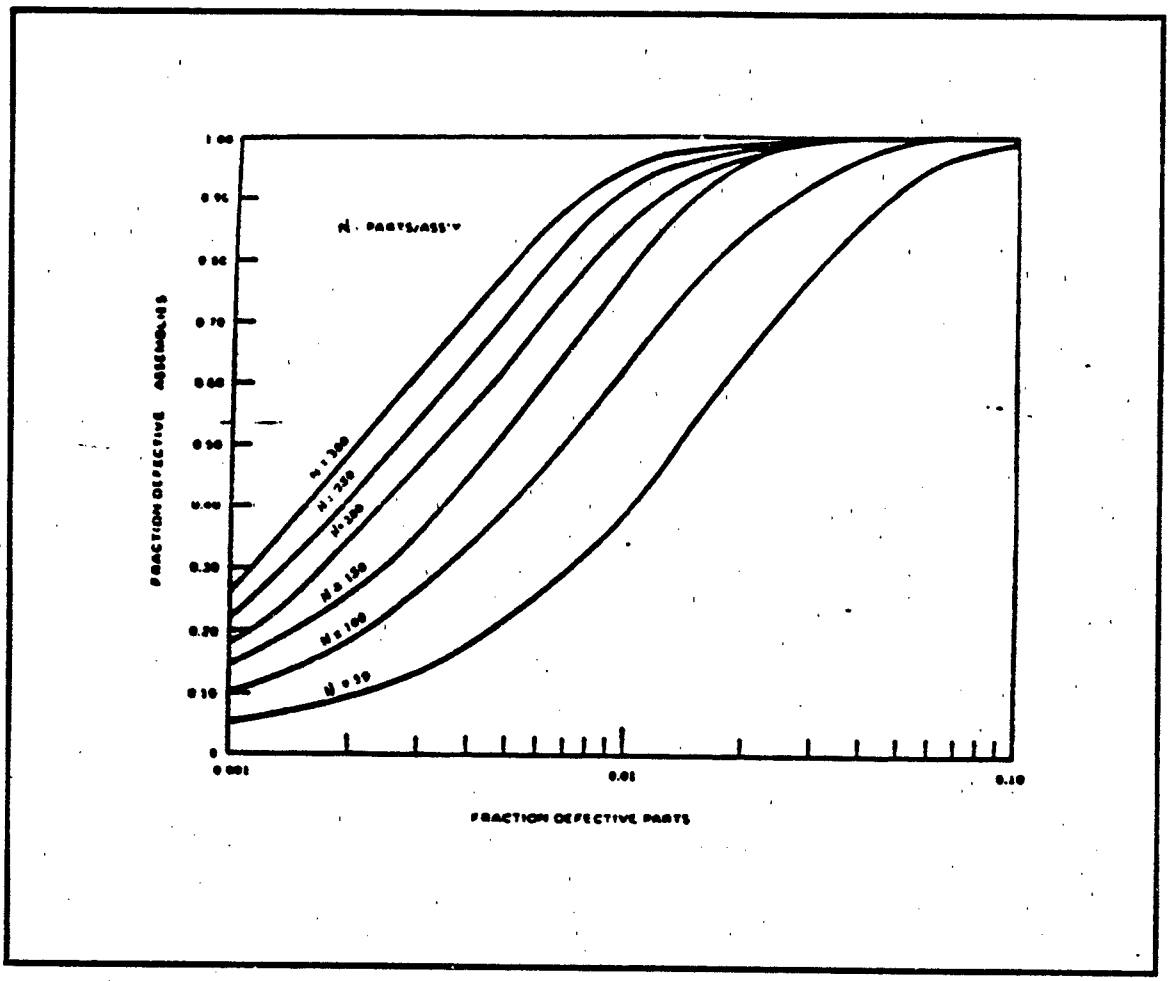


Figure 4.2 Fraction of Defective Assemblies vs Remaining Part Fraction Defective

defect density depending upon the number of parts contained in the assembly. As an example, for a 150 part assembly containing parts with a Defect density of .01 (10,000 PPM), the assembly defect density is 1.5. In terms of yield, only about 22% i.e. exp(-1.5) of such assemblies, when subjected to first assembly test, would pass without failure. It is quite obvious that the part defect density must be much better than .01 if the costs of rework, retesting and handling of the assemblies are to be avoided. The questions answered by the ESS methodology and procedures in this handbook are: How much better must the remaining part defect density be?; What level of part defect density is needed for delivered systems? and, can such levels be achieved?

4.4.3.3.2 Part Level vs. Assembly Level Screening. Screening at the part level may be a cost effective alternative for eliminating defects prior to the parts being assembled into the production hardware. A population of parts, even those procured to high quality levels, may appear to contain high defect density levels. For example, microelectronic devices procured to the quality requirements of MIL-STD-883 receive 100% final electrical testing by the part vendor. Nonetheless, one manufacturer has found that about 1%, and as much as 4% of the parts will not pass a similar electrical test performed at the OEM receiving inspection. There are several possible reasons for this including:

- the seller's and buyer's tests are different
- seller testing errors
- buyer testing errors
- device damage or degradation in handling
- inspection and sorting errors.
- latent defects

General awareness of this problem in the industry has resulted in improvements in part quality and reliability and the results may no longer be applicable. For example, results reported in the Integrated Circuit Screening Report published by the IES in November, 1988 indicated a significant improvement for microcircuits and revealed that the additional handling involved in the rescreening process was actually introducing more defects that were being screened.

None the less, it should be noted that the foregoing discussion addresses errors only and must be extended to include latent defects and that it is primarily latent defects that escape to the field and degrade early life reliability.

The requirement for parts rescreening should not be mandated and should only be used as determined to be necessary by the implementation of the Handbook.

Screening at the assembly level is also a means of finding and eliminating part defects from the hardware. The part fallout from early screening at the assembly level can provide much of the information needed for resolving such uncertainties and taking corrective action. There are always uncertainties as to whether the part defects which are found during assembly level screening, are escapes from part level screens or whether they are newly introduced defects due to handling, test and assembly operations. A thorough failure analysis of the fallout from assembly level screening can help in determining defect causes and the types of screens which should be used.

4.4.3.3.3 Air Force R&M 2000 ESS Policy-Part Fraction Defective. Air Force R&M 2000 ESS studies recommend that the manufacturing process begin with piece parts having a remaining part fraction defective below 1000 PPM by FY87 and below 100 PPM by FY90. Procedure D of Section 5 and ESS results are used in the Handbook procedures to evaluate the achievement of these goals. However, the prescribed requirement of 100 PPM defect level for parts may not be adequate for achieving the required reliability. The actual requirements should be determined using Procedure A and may increase or relax the R&M 2000 levels. The R&M 2000 levels should also be interpreted as being applicable to both latent and patent defects where the patent defects include errors due to electrical testing, test correlation, specification discrepancies etc.

4.4.3.3.4 Process Maturity and Defects. The maturity of both the product design and the manufacturing process can significantly impact the quantity and type of defects which can reside in the hardware. The data shown in Table 4.2 represent experience on several large development and production projects. As the data illustrate, the proportions of failures in a product which are traceable to design, part or manufacturing causes can differ substantially, depending upon the stage of maturity of the product and the manufacturing process. During the development phase, the major contributor to product failure is design (50%), while parts may account for 20% of the failures. Unfortunately, design problems can still be present in the product when stress screens are being conducted during production.

The proportion of failures in a product, attributable to design, would be expected to decrease as the process matures. The overall defect density in the product would also be expected to decrease as the process matures. Maturity of the product and process should be taken into account when planning estimates of defect density are being determined in accordance with Procedure B of Section 5. In such cases, the user may decide to use Procedure D to modify the defect density values in Tables 5.2 through 5.13, of Procedure B either upward or downward, depending upon past experience and assessments of maturity. With an emphasis on TQM and concurrent engineering, more thorough design analysis and assessment should be performed during the design stage to prevent design problems during production. A high incidence of design problems during initial production provides valuable feedback on the efficacy of the concurrent engineering program.

Table 4.2 Defect Types & Density vs Process Maturity

Maturity	Defect Type Distribution (percent)			Defect Density
	Design	Manufacturing	Parts	
Development	40-60	20-40	10-30	High
Early Production	20-40	30-50	20-40	Moderate
Late Production	5-15	20-30	60-70	Low

4.4.3.3.5 Packaging Density. Assemblies with high part and wiring density are more likely to contain both patent (error) and latent defects because of the proximity of devices and interconnections contained within a small volume. The

effects of poor heat dissipation in densely packaged electronic assemblies can accelerate latent defects to early failure. Difficulties in initially assembling or reworking the hardware can also make such assemblies more defect prone. Procedure B in Section 5, for estimating defect density, thus includes a packaging density factor. This factor should be continually monitored and refined using Procedure D of section 5.

4.4.4 Screen Selection and Placement. Planning a stress screening program requires the selectionand placement of appropriate screens at various levels of assembly so as to achieve a cost effective screening program. Listed below are the factors which affect screen selection and placement. The factors are discussed in more detail in the following paragraphs.

a. Screening strength - The product of precipitation efficiency and detection efficiency, determines the capability for removing defects.
b. Precipitation efficiency - Prior knowledge of the effectiveness of the screens in precipitating defects to failure.
c. Detection efficiency - The tests which can be economically and feasibly used to detect defects which have been precipitated to failure by the screens.
d. Thermal and vibration response characteristics - The structural, thermal and material properties of the items to be screened and their response to applied stress.
e. Design limits - The environmental stress design limits of the items to be screened.
f. Facilities - The screening, test and instrumentation facilities available to the manufacturer to perform screening and test operations.
g. Costs - The costs to achieve screening program goals on remaining defect density.
i. Product Reliability Verification Test (PRVT) - The use of a PRVT as an integral part of an ESS program to provide confidence field reliability will be achieved.

4.4.4.1 Precipitation Efficiency. Precipitation efficiency is defined as the probability that a screen will precipitate a defect to a detectable state given that a defect susceptible to the screen stress is present. Screening strength is defined as the precipitation efficiency multiplied by the probability that the defect will be detected and removed (i.e., the detection efficiency). A basic premise of stress screening is that under specific screening stresses applied over time, the failure rates of defectives are accelerated from that which would occur under normal field operating stress conditions. By subjecting electronic items to accelerated stresses, i.e. rapid temperature cycling and random vibration, latent defects are thus precipitated to early failure. More severe stresses will tend to accelerate failure mechanisms and the rate of defect failure. For example, the failure rate of a latent defect increases with more rapid rates of temperature change and larger temperature extremes. The precipitation efficiency (and hence screening strength) of a random vibration screen increases as a function of the level and duration of the applied excitation.

Stress screens are not all equally effective in transforming latent defects into detectable failures. Table 4.3 provides a listing of latent defect types and the screens believed to be effective is precipitating them to failure. Table 4.3 may be used as an aid in the selection of a screen type when prior knowledge on workmanship or part defects for similar assemblies is not available.

Table 4.3 Assembly Defect Types Precipitated by Thermal & Vibration Screens

Defect Type	Thermal Screen	Vibration Screen
Defective Part	X	X
Broken Part	X	X
Improperly Installed Part	X	X
Solder Connection	X	X
PCB etch, Shorts and Opens	X	X
Loose contact		X
Wire Insulation	X	
Loose wire termination	X	X
Improper crimp or mating	X	
Contamination	X	
Debris		X
Loose hardware		X
Chafed,pinched wires		X
Parameter drift	X	
Hermetic seal failure	X	
Adjacent boards/parts shorting		X

Reference RADC-TR-82-87

Table 4.3 indicates that vibration screens are generally more effective for loose contacts, debris and loose hardware while temperature cycling screens are not effective. Thermal screens are generally more effective for part parameter drift, contamination and improper crimp or mating type defects while vibration screens are not. For other defect classes listed in the table, both thermal and vibration screens are effective, but the relative degree of effectiveness of one screen type over the other is not precisely known. These are some of the uncertainties which must be dealt with in planning a screening program. Historically, on average, 20% of the defects are found to be responsive to vibration screens and 80% to temperature cycling screens. (Reference publication IES Environmental Stress Screening Guidelines for Assemblies).

To improve the modelling accuracy and to ensure a proper balance between thermal and vibration screens, it is recommended that the defect population be segregated

into RV sensitive defects and TC sensitive defects. If necessary, the population responsive to either TC or RV can also be included on the model.

4.4.4.1.1 Screen Parameters. Precipitation efficiency is a function of specific screen stresses (parameters) and the time duration of the stress application. Equations provided in Procedure C of Section 5 provide values for precipitation efficiency as a function of relevant screening parameters. It should be noted that these parameters pertain to the unit under test and not the chamber etc. Vibrational characteristics of the equipment (eg. resonances, transmissibility etc.) and the various thermal conductivities and masses must be considered. All assembled hardware consists of many paths along which a stress might be transmitted. The selection of screening parameters and methods of stress application must be suited to the stress transmission characteristics of the hardware design. As a part of the screen selection and placement process, in which thermal or vibration screens are to be used, a stress response survey of the item to be screened should be performed. This may require simulations and or surveys conducted on the actual or similar hardware. Care should be exercised to ensure that hardware responses are large enough to generate an effective screen while not exceeding hardware design capability. Environmental stresses should be applied to the hardware and the response of critical hardware elements measured to determine whether maximum or minimum temperature limits are being exceeded, and whether suspected defect sites (parts, interconnections etc.) are responsive to the screen stress. In addition, normal design provisions for isolating the hardware from stress such as the use of shock mounting, vibration isolators or cooling air should also be evaluated. Application of environmental stress screening in such instances, should require bypassing the normal stress isolation provisions or may dictate the need for screening at lower assembly levels which do not include the stress isolation design features. Temperature cycle, constant temperature, random and swept-sine screening parameters are defined as follows:

a. Thermal cycle screen parameters

(1) Maximum temperature (T_{max}) - The maximum temperature to which the screened item will be exposed. This should not exceed the lowest of the maximum ratings of all the parts and materials comprising the item. Note that non-operating temperature ratings for parts are higher than operating ratings.

(2) Minimum temperature (T_{min}) - The minimum temperature to which the screened item will be exposed. This should not exceed the highest of the minimum ratings of all the parts and materials comprising the assembly.

(3) Range (R) - The range is the difference between the maximum and minimum applied external (chamber) temperature. (T_{max} - T_{min}). Temperatures are expressed in °C.

(4) Temperature rate of change (T) - This parameter is the average rate of change of the temperature of the item to be screened as it transitions between T_{max} and T_{min} and is given by:

$$T = \left[\left(\frac{T_{max} - T_{min}}{t_1}\right) + \left(\frac{T_{max} - T_{min}}{t_2}\right)\right] \div 2$$

Where: t_1 is the transition time from T_{min} to T_{max} in minutes

t_2 is the transition time from T_{max} to T_{min} in minutes

(5) Dwell - Maintaining the hardware temperature constant, once it has reached the maximum (or minimum) temperature, is referred to as dwell. The duration of the dwell is a function of differences in the thermal mass of the items being screened.

(6) Number of cycles - The number of transitions between temperature extremes (Tmax or Tmin) divided by two.

b. Constant Temperature Screen Parameters

(1) Temperature delta (Δ T) - The absolute value of the difference between the hardware temperature and 25°C.

$$\Delta T = |T - 25\ °C|$$

Where T is the hardware temperature

(2) Duration - The time period over which the temperature is applied to the item being screened, in hours, after the hardware has reached thermal equilibrium.

c. Vibration Screen Parameters

(1) Grms level for random vibration - The rms value of the applied power spectral density observed by the hardware, including resonance and transmissibility effects.

(2) G-level for swept sine vibration - The constant rms acceleration applied to the equipment being screened throughout the frequency range above 40HZ. The g-level below 40HZ may be less.

(3) Duration - The time period over which the vibration excitation is applied to the item being screened, in minutes.

(4) Axes of vibration - This can be a single axes or multiple axes depending on the sensitivity of defects to particular axial inputs.

4.4.3.1.2 Design Limits. The use of screen parameters which impose stresses which exceed the design limits of the product is not recommended. Effective screening

programs can be developed without having to resort to stresses which exceed the design capability of the hardware. Criteria for judging how much the design limits can be safely exceeded, without causing damage to the product, are non-existent or at least arbitrary. However, to permit reasonably high ESS stress levels, it is important that the equipment be designed for ESS and thus the ESS program and required stress levels should be determined concurrently during the design stage. Using the procedures contained in the handbook, the manufacturer can focus on those items in which defects are most likely to reside in the hardware and determine safe screening levels, within appropriate cost constraints, for precipitating them to failure. The procedures take into account the increased defects with increased factory stress level and also require a fatigue life study to ensure that useful operating life has not been impacted by the amount or level of ESS.

4.4.4.1.3 Guidelines for Initial Screen Selection and Placement. The development phase ESS program is intended to expose various defect types and causes and to obtain factory data to calculate and refine the planning estimates of D_{IN} and SS that were based on handbook and industry data. Additional ESS beyond that intended for production may be required to improve the estimate accuracy. An initial screening regimen should be selected for experimental use during the development phase in conjunction with the use of the handbook procedures. Table 4.4 is recommended as an aid in selecting and placing screens for a starting regimen.

4.4.4.1.4 R&M 2000 ESS Initial Regimen. R&M 2000 ESS studies recommend the screen types, parameters and placements outlined in Table 4.5 as an initial regimen. The screens contained in Table 4.5 have high precipitation efficiency. After sufficient fallout has been observed, the screening regimen may be reduced.The R&M 2000 guidelines thus represent initial values for consideration during the development phase and can be reduced for production based on the planning and analysis procedures outlined in Procedures A and D.

4.4.4.2 Detection Efficiency. Detection efficiency is a measure of the ability to detect and remove patent defects. Detection efficiency includes factors representing fault coverage, the requirement for concurrent stress, the test duration, and the diagnostics and rework capabilities for removing the defect. Detection efficiency is expressed as the ratio of patent defects detected (and removed) by a defined test procedure to the total possible number of patent defects. While stress screens may be effective in precipitating a latent defect into a detectable failure, removal of the failed condition is dependent on the capability of the test procedures used to detect and localize the failure.

Care should be taken to ensure that tests have detection efficiencies as high as is technically and economically achievable. The screens may otherwise precipitate defects to failure which may go undetected by post screen tests. Modern electronic equipment comprised of microprocessors, large memory and LSI devices may contain defects so subtle that only the most thorough of tests can detect them. High screening strengths at lower levels of assembly may not always be easily accomplished because of low detection efficiency. The difficulty in accurately simulating functional interfaces or the inability to establish meaningful acceptance criteria may make the development of tests with high detection efficiency at the assembly level difficult and costly. A certain percentage of defects may only be detectable at the unit/system level when all or a majority of the system components are connected and operating as a system. Analysis and

quantification of detection efficiencies should be an integral part of the planning for a screening program.

Table 4.4 Guidelines for Initial Screen Selection and Placement

Level of Assembly	Selection				Placement	
	Temp Cycle	Const. Temp.	Rand Vib.	S.S. Vib.	Advantages	Disadvantages
Assy	E[1]	M[2]	M[3]	N	• Cost per flaw precipitated is lowest (unpowered screens) • Small size permits batch screening • Low thermal mass allows high rates of temperature change • Temperature range greater than operating range allowable	• Test detection efficiency is relatively low • Test equipment cost for powered screens is high
	E = Effective M = Marginally Effective N = Not Effective Notes: 1. Particularly if power is applied and performance is monitored at temperature extremes. 2. Effective where assemblies contain complex devices (RAMs, microprocessors, hybrids) 3. Effectiveness highly dependent on assembly structure. Not effective for small, stiff PWAs.					
Unit	E	M	E	M	• Relatively easy to power and monitor performance during screen • Higher test detection efficiency than assembly level • Assembly interconnections (e.g., wiring backplane) are screened	• Thermal mass precludes high rates of change, or requires costly facilities • Cost per flaw significantly higher than assembly level • Temperature range reduced from assembly level
System	E	M	E	M	• All potential sources of flaws are screened • Unit 'properability' /lass data can • High test detection efficiency	• Difficult and costly to test at temperature extremes • Mass precludes use of effective vibration screens, or makes use costly • Cost per flaw is highest

4.4.4.2.1 Determining Detection Efficiency. Detection efficiency is determined as the product of factors that represent the following considerations:

(a) The probability of observing and detecting a patent defect. This includes the probability of detection and the probability of occurrence. Consideration must also be given to the extent that the tests and limits being used represent all application requirements for functional and parametric performance. The detection of intermittent and/or situation sensitive defects may also require extended test times and may be modelled using a Poisson distribution.

(b) The requirement for concurrent stress. Many of the latent flaws precipitated to failure by ESS can only be detected when stress is applied during the test.

(c) The probability of isolating and then removing the defect without creating an additional defect.

Table 4.5 R&M 000 Environmental Stress Screening Initial Regimen

SCREEN TYPE PARAMETERS AND CONDITIONS	ASSEMBLIES (PRINTED WIRINGS ASSEMBLIES) (SRU)	EQUIPMENT, OR UNIT (LRU/LRM)
THERMAL CYCLING SCREEN		
Temperature Range (Minimum) (see Note 1)	From -54°C To +85°C	From -54°C To +71°C
Temperature Rate of Change (Minimum) (see Note 2)	30°C/Minute (Chamber Air Temp)	5°C/Minute (Chamber Air Temp)
Temperature Dwell Duration (See Note 3)	Until Stabilization	Until Stabilization
Temperature Cycles (Minimum)	25	10
Power On/Equipment Operating	No	(See Note 5)
Equipment Monitoring	No	(See Note 6)
Electrical Testing After Screen	Yes (At Ambient Temp)	Yes (At Ambient Temp)
QUAS-RANDOM VIBRATION (See Note 7)		
Spectral Density	(See Note 8)	6 Grms
Frequency Limits		100-1000 HZ
Axes Stimulated Serially or concurrently		3
Duration of Vibration (Minimum)		
-Axes stimulated serially		10 Minutes/Axis
-Axes stimulated concurrently		10 Minutes
Power On/Equipment Operation		(See Note 5)
Equipment Monitoring		(See Note 6)

On some system procurements the probability of detection is a specified parameter for built-in-test (BIT), performance monitoring (PM) and fault location (FL) capability requirements. When the required BIT or PM/FL capability is used to verify performance of an item being screened, the actual values of fault coverage should be used in conjunction with the factors defined above and in Procedure C. On other system procurements, requirements to perform a failure modes and effects analysis (FMEA) are specified in the contract. In such cases, the FMEA should be used to estimate the fault coverage for a given test design.

When FMEA or BIT fault detection requirements are not specified in the contract, estimates of fault coverage should be made based upon experience data. Appendix C provides values of fault coverage for various tests which may be applied with stress screens. The values in the table were derived by production and engineering test personnel from a large DOD electronic system manufacturer. RADC TR-82-87

4.4.3.2.2 Power-On Testing vs Power-Off. Application of power, exercising and monitoring equipment performance continuously during the screen will greatly enhance detection efficiency. Subtle faults, such as contact intermittents or temperature sensitive parts, can only be detected with powered and monitored screens. With the increased complexity of modern electronics, fault sites may be confined to smaller areas and fault symptoms may appear only during certain tests or under a special set of external conditions. As a result, a greater incidence of "Cannot Duplicate"(CND), "No-Fault Found" (NFF) and "Retest OK"(RTOK) and similar intermittent or transient phenomena can occur. Patent defects which have been precipitated to failure by stress screens can be categorized into three general types:

a. Type 1 Physical defects transformed from an inherent weakness to a hard failure by the stress screen.

b. Type 2 Physical defects that manifest as failures only while under thermal or mechanical stress. (e.g. intermittent caused by a cold solder joint).

c. Type 3 Functional defects that manifest as performance failures or anomalies only while under thermal or mechanical stress. (e.g. timing problems).

The type 1 defects are readily detected by post screen tests of sufficient thoroughness. Type 2 and Type 3 defects require thorough and continuously monitored tests so that they can be detected. Type 3 defects, which include problems such as timing, part parameter drift with temperature or tolerance build-up can only be detected with powered and monitored tests. Type 2 and Type 3 defects can comprise 50% and as much as 80% of the latent defects present in the hardware. (Reference RADC TR-86-149)

Developing tests and test strategies for use with stress screens and estimating their detection efficiency is a vitally important activity in planning a stress screening program. The use of tests with high detection efficiency is of equal importance to using screens with high precipitation efficiency in structuring a screening program for production.

4.4.4.2.3 Pre/Post Screen Testing and Screening Strength. In order to experimentally determine screening strength, the following conditions are required:

a. The items subjected to stress screening must be tested thoroughly before the stress screen to assure that no detectable failures remain at the start of stress screening. When testing is not performed prior to stress screening, it is not known whether patent defects were present, which could have been detected without stress screening, or whether latent defects were precipitated by the stress screen.

b. The items subjected to stress screening must be powered and exercised. Performance must be continuously monitored to assure that stress-dependent defects (e.g., intermittents, temperature and timing sensitive faults) are detected.

c. The items subjected to screening must be tested using the same test(s) both before and after the stress screen to assure that the failures detected are a result of the stresses imposed.

d. Data must be collected on defect fallout after the stress screen (i.e. , during subsequent stress screens, tests, or early field operation) to obtain an estimate of the number of defects which were initially present.

When such data are available and assuming perfect tests, then the screening strength can be determined by use of the observed fallout from the screen and the number of defects initially present i.e.:

$$\text{Screening Strength} = \frac{\text{Fallout}}{\text{Number of Initial Latent Defects}}$$

However, the total number of latent defects can not be determined until extensive field data is available. We are thus compelled to use a modeling approach where screening strength is based upon estimates derived from a combination of the actual screening program data, experiments, and the published literature. The precipitation efficiency models and values used in the handbook tables of Procedure C in Section 5, were developed using such an approach. The results and methodology used for these studies are contained in RADC TR-82-87 and RADC TR-86-149. Additional information is also provided in AFWAL TR-80-3086 and ADR 14-04-73. As more experience data on stress screening are gathered, the screening strength estimates will be refined and improved.

4.4.4.2.4 Pre and Post Screen Testing During Production. Performing tests before, during, and after environmental exposure, as discussed in 4.4.4.2.3, may be useful during the development phase but represents an undesirable non-value added expense during production. An alternate method is required. The analysis methodology provided in Procedure D is based upon curvefitting actual data to determine the latent and patent defect components. Defects present before screening appear as the Dp term and defects precipitated and detected by the screen appear as the D_L term. This approach, however, requires a sufficient number of

data points throughout the screen. If changes take place during production such as in an assembly or fabrication process, personnel or production flow, then the defect density (both latent and patent) is likely to change and affect the fallout observed during screening and will be apparent using the monitoring and control procedures of Procedure E. Under long term production, process improvements and other corrective actions taken as a result of the screening process are likely to change the quantity and distribution of latent defects present in the hardware.

4.5 Production Phase - Monitoring Evaluation and Control. Once a screening program is implemented during the production phase, the screen fallout data and the screening process must be monitored and controlled to assure that program objectives are achieved. For an effective monitoring and control program, the field reliability requirements should be directly related to goals and requirements for parts, processes, and materials and assemblies for all factory integration and ESS test levels. The procedure for establishing these requirements and for monitor and control are provided in Procedures A and E respectively. Use of a Failure Reporting Analysis, and Corrective Action System (FRACAS) should be an integral part of production phase monitoring and control tasks. The fallout from the screening process provides the necessary visibility regarding the sources of defects in the product and the manufacturing process. Finding defects, determining their root causes and ensuring that the sources of the defects are eliminated from either the process or product, is the basic mechanism by which process capability is improved.

Analyses of screen fallout data must be performed with specific objectives in mind. Well-defined monitoring, evaluation and control task objectives will ensure that the proper data is collected, classified and correctly analyzed to meet objectives. The objectives of the monitoring-evaluation and control tasks are to establish assurance that remaining defect density and reliability goals are achieved through implementing improvements in manufacturing, screening and test process capability. Manufacturing process capability is improved through taking corrective actions which reduce the number of defects that are introduced into the product. Screening process capability is improved by increasing both the precipitation efficiency of screens (by ensuring that potential sites for defects in the product are being adequately stimulated) and the detection efficiency.

Another goal of monitoring and control is related to cost effectiveness. The initial screening program might have been based upon planning estimates which were overly pessimistic. Corrective actions might also have been taken during production to reduce the number of defects introduced into the product. In either case, if the screening program is continued as planned, more screening than is necessary results, which impacts both cost and schedule. Decisions must be made on how to reduce the screening regimen. In a sense, the goal of ESS and the monitoring and control tasks is to make the screening program unnecessary (except for that limiting value required for PRVT).

4.5.1 Data Collection. The importance of timely and accurate data collection to achieving screening program objectives cannot be overemphasized. The data elements listed below should be collected during the conduct of the screening program. Some of the data elements become available directly as observed events from the screening process. Other data elements will become available only after analysis of the failures and failure data, or after a batch of items have been exposed to screening.

a. Identification of the items exposed to the screen/test,e.g., description, part number, revision, and serial number.

b. Number of like items exposed to the screen/test.

c. Number of like items passed/failed the screen/test.

d. Date of test

e. Test station or equivalent

f. Type and number of defects found in conjunction with the number of items exposed, passed/failed (data elements b, c, d).

g. Description of the type of defect found (part, workmanship/process, design)

h. Identification of the part, interconnection site where the defect was found.

i. Identification of the assembly level or manufacturing process operation where the defect was introduced.

j. Screen conditions under which the defect was found (e.g., high temperature, vertical axis of vibration etc.).

k. Time-to-failure relative to the start of the screen.

l. Failure analysis results which identify the root cause of the defect.

m. Corrective action taken to eliminate the cause of the defect from the product and/or process.

Data elements l and m may only be available if trends, as identified by the SPC monitoring and control methodology, warrant detailed root cause analysis and corrective action.

4.5.2 Failure Classification. In order to establish a basis for the analysis of the screening fallout data, the failures must be properly classified. The following classification scheme is recommended.

a. Part defect -- A failure or malfunction which is attributable to a basic weakness or flaw in a part (diode, transistor, microcircuit, etc.) Subcategories may include electrical, electronic, and mechanical.

b. Manufacturing defect - A failure or malfunction attributable to workmanship or to the manufacturing process (cold solder joint, cracked etch, broken wire strands, etc.) Subcategories may include assembly, process, and handling.

c. Design Failure - A failure or malfunction attributable to a design deficiency. Note that electrical or thermal overstress failures due to inadequate derating, are design problems. Subcategories include hardware and software.

d. Externally induced failures - A failure attributable to external influences such as prime power disturbances, test equipment, instrumentation malfunctions or test personnel.

e. Dependent failure - A failure which is caused by the failure of another associated item which failed independently.

f. Unknown cause failure - An independent failure which requires repair and rework but which cannot be classified into any of the above categories. An intermittent failure that recurrs infrequently would be an unknown cause. Subcategories include verified and not verified.

g. Unable to verify (UTV), retest ok (RTOK), and NO Fault Found (NFF) classifications describe conditions where an anomaly during testing could not be reproduced.

4.5.3 Preliminary Analysis of Fallout Data. A preliminary analysis of the fallout data should be performed to insure that failure causes are properly established and to categorize the failures so that more detailed analysis related to the ESS program objectives can be performed.

a. All failures traceable to part board and interconnection defects, which are precipitated and detected by a screen/test, should be considered to be latent defects provided that pre-screen testing was performed. These data should be used for monitor and control purposes.

b. A predominance of design problems which are discovered during production screening operations is a matter of serious concern. Every effort should be made to determine corrective actions for design problems very early in production. It does no good to speculate that the design problems should have been eliminated from the hardware during the development stage. Stress screening, on a 100% basis, is an expensive and time consuming method for finding design problems. If the fallout from screening indicates persistent evidence of design problems, methods other than 100% stress screening should be used. Reliability growth and Test-Analyze-And-Fix (TAAF) techniques are recommended.

c. Special attention should be given to unknown cause failures. Sufficient investigation should be made to establish that an intermittent condition does not exist. The number of failures classified as "Unknown Cause" should be kept to a minimum. Every effort should be made to correlate the failure circumstance data with the other similar failure incidents, as well as to use failure analysis so as to establish the cause of failure. The number of "unknown cause" classifications and/or "unable to verify" classifications should be used in assessing the detection efficiency.

d. Analyses of induced failures should be performed to determine necessary corrective actions.

The detailed analyses would typically be performed if the established goals and requirements are not being achieved, either for parts, materials and processes or for assemblies at various ESS levels.

4.5.4 Analysis of Screen Fallout Data. The analysis of screening fallout data is directed toward evaluating the screening process so as to achieve screening program goals on remaining defect density $D_{REMAINING}$. Yield goals are achieved by both improving manufacturing process capability through corrective action and by improving the screening and test process capability when it is found to be needed.

Manufacturing, screening and test process capability will determine the remaining defect density. The capability of these processes are measured and controlled by use of two important quantities, the incoming defect density (D_{IN}) and the screening strength (SS). Neither one of these quantities are directly observable as a result of the screening process. The only observable statistic is the fallout from the screen/test, from which inferences regarding D_{IN} and SS must be drawn. The basic approach used in Procedure D of Section 5, is to obtain estimates of D_{IN} and SS, using the screen fallout data and to statistically compare the observed data against the planning estimates. Based upon the comparisons, corrective actions are determined to eliminate the source of the defect from the process and/or to change the screens so as to achieve stated objectives.

Two complementary procedures are presented in Procedures D and E for performing monitoring and analyses tasks. Procedure D uses curve fitting techniques, applied to the mathematical model, to estimate D_{IN} and SS. Procedure E uses Quality Control Charts (SPC and PARETO) for monitoring and control.

Quality control charts. The use of control charts for defect control is a standard technique. Control charts (SPC and PARETO) are used in Procedure E which are based upon the Poisson Probability distribution; i.e.,

$$P(x) = \frac{e^{-D} D^{x}}{x!}$$

Where: D = defect density
x = number of defects in an item
$P(x)$ = probability of x defects in an item

The mean of the Poisson distribution is D and the standard deviation is $\sqrt{D}$. The primary purpose of the control chart technique is to establish baselines against which the process can be monitored and by which out-of-control conditions can be identified. Because of varying conditions, for example improving defect density, the actual defect density, D is determined using regression analysis. This value is then used to determine the expected statistical variation due to limited sample size

$$\text{i.e. } D \pm n\sqrt{\frac{\overline{D}}{N}}$$

where n is the number of standard deviations, typically 3, and N is the sample or lot size.Defect density is calculated, using the fallout data, and compared against the control chart baselines. Part and workmanship (process) problems are rank ordered with consideration for the expected defects based on complexity etc. and

analyses are performed and corrective actions taken to eliminate the source of the defects from the product. Procedure E of Section 5 contains the detailed methodology for implementing the control chart technique.

4.5.4.1 Use of the Mathematical Model to Evaluate Screening Results. Appendix A provides a description of the Stress Screening Mathematical Model. The factory fallout data (expressed defects per system) can be curve fitted to the expression developed therein (for $D_{REMOVED}$) so as to obtain estimates of the model parameters. Parameters which can be determined using this method are D_{IN}, SS (comprising PE and DE terms), the constant failure rate (CFR) and SAF, a stress adjustment factor relating defect levels at field stress to factory stress.

4.5.4.2 Use of the Chance Defective Exponential (CDE) Model to Evaluate Screening Results. The defect distribution for both factory and field stress environments have been empirically determined to be represented by the following expression.

$$Dremoved = DE.[\ Dp + Dl.(1-e^{-kt}) + CFR.t\ ]$$

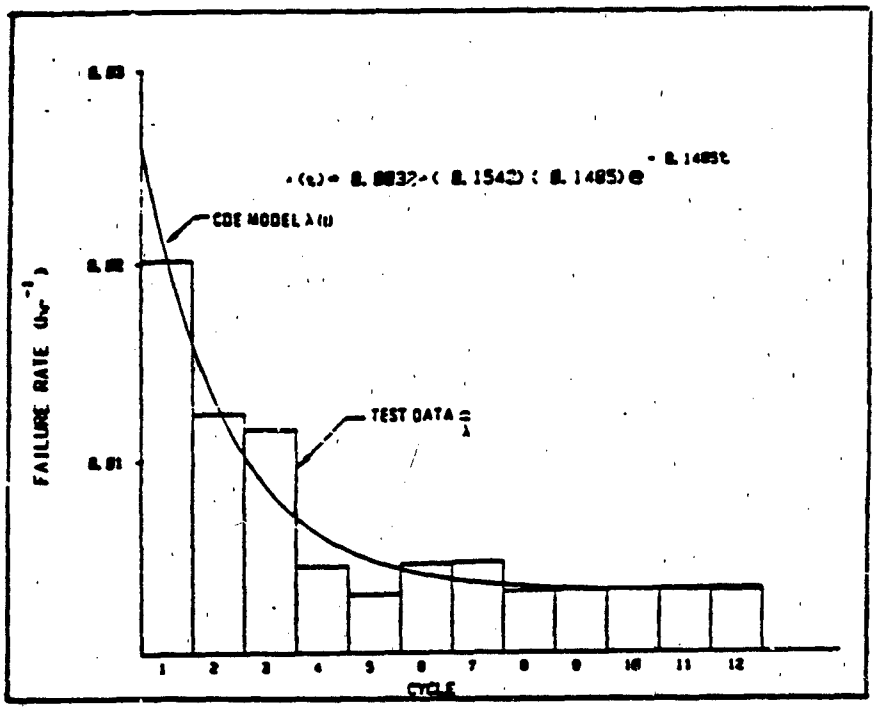
where Dp represents the patent defects, Dl represents the latent defects, t the stress duration eg time, cycles etc, k the precipitation stress constant, CFR the constant failure rate, and De is the detection efficiency which is 1 for the field.

The CDE model developed by Fertig and Muthy and discussed in a paper contained in the 1978 Annual R&M Symposium provides a possible explanation for this observed relationship.

Regardless of the true derivation, the empirical results have been found to be sufficiently accurate for the purposes of this handbook. Inaccuracies either in the modelling and or the estimated parameters are initially addressed using design margins and addressed during the production phase through the use of actual factory and field data to refine the estimates. The observed fallout data can be fitted to the model to obtain estimates of the model parameters. The parameters of the model provide estimates of the incoming defect density DIN, the screening strength (SS, PE, DE), the limiting failure rate of the equipment (CFR) and the stress adjustment factor (SAF). Figure 4.3 is an extract from a study report which shows a histogram of the screen fallout from a 12 cycle -54°C to 71°C temperature cycle screen. The fallout per cycle is used to obtain maximum likelihood estimate (MLE) for the parameters of the CDE model.

As Figure 4.3 shows, the CDE model parameters estimated by the MLE procedure, are: incoming defect density (DIN) equal to .1542 defects per item, the failure rate of a defect (Dk) equal to .1485 failures per hour (which corresponds to a screening strength of .95) and a value of .0032 for the limiting failure rate (CFR).

4.5.4.3 Product Reliability Verification Test (PRVT). The use of a PRVT segment as part of an ESS program is intended to provide confidence that field reliability will be achieved and help identify out of control conditions that could otherwise be missed. As defect density is improved, ESS can be reduced to optimize cost without impacting field reliability. However, ESS can not be completely eliminated since some portion is required to allow reliability to be assessed. PRVT is that portion of ESS retained for this purpose.



Reference AFWAL-TR-80-3086

Figure 4.3 Temperature Cycling Data Fitted to the Chance Defective Exponential Model

Assessments of reliability should be made on the basis of the performance of the collective population. The PRVT segment should be implemented on a first pass yield basis (first pass yield being defined as the number of systems completing the PRVT segment with no failures divided by the total number of systems submitted first time). If the first pass yield requirements are not achieved, corrective actions must be taken that address the entire population. Appendix B provides the mathematical derivation of the PRVT methods contained in the handbook. Procedure F in Section 5 contains the detailed procedures for incorporating the PRVT segment.

Note that a failure free requirement for any part of ESS or PRVT is not recommended. If requirements (eg. PRVT yield) are not being achieved and defects are randomly distributed, then the overall defect density is too high and action must be taken that affects the entire population. Requiring one particular piece of equipment to pass a sequence of tests "failure free" does not substantially improve the reliability of the population. The failed item however, must undergo

sufficient confidence testing subsequent to rework to ensure that the fault has been eliminated.

4.6 Costs of ESS vs Productivity Improvement. The costs of conducting a screening program during the production phase can be high. To a large extent, the costs can be offset by the increased productivity which results through proper screen selection and placement. Screening at the lowest possible level of assembly will almost always be the least costly alternative in terms of rework costs. The time and effort required to test, troubleshoot and repair items increases by at least an order of magnitude at each subsequent level of assembly. Significant cost savings or avoidance can accrue to the manufacturer by analyzing the cost benefits of various screen selection and placement alternatives and by striving to find defects at the lowest possible level of assembly. The fixed and recurring costs to screen, instrument and test the hardware at lower assembly levels, especially with power applied, can possibly, negate any benefit from lower rework costs thus, the optimum ESS program must be determined for each equipment type. Cost savings to the Government will result through improved field reliability and corresponding reductions in field repair costs. The benefits of a properly conducted ESS program to the Government go beyond field repair costs alone. Improved reliability during early life will also reduce over-buying of spares, since estimates of required spare quantities are based upon early life field performance. The opportunity for introducing new defect sources into the hardware during field maintenance and handling is also reduced.

There should be however, controls and constraints on the cost of conducting a screening program. Situations can arise where the cost of conducting a screening program far outweigh any benefits which may be derived. For example, for low complexity items the number of screenable defects which are likely to be present in the hardware may be relatively small. Conducting a full-scale screening program, in such cases, can result in very high costs per defect eliminated. Costs of $10K to $15K per defect eliminated may be justified for equipments which are used in critical missions with very high reliability requirements. On the other hand, such costs may be difficult to justify if the equipment is used in noncritical missions and if the costs of field maintenance are not severely effected by not screening. Each case, where a stress screening program is under consideration, must be judged individually as to the cost benefits to be derived from stress screening and optimized on a combined user-producer cost basis. Procedure A, in Section 5 is used to determine the cost effectiveness of ESS programs.

4.6.1 Facilities and Costs. The facilities that the manufacturer has available for screening, instrumenting and testing the product affects screen selection and placement. A manufacturer may not have random vibration facilities or automatic test systems which can be used for the stress screening program. In such cases, the manufacturer may decide to impose less severe stresses for a longer duration or decide to use less expensive alternatives such as described in NAVMAT P-9492. The costs to purchase expensive screening or test equipment and perform screens at a given level of assembly may not be warranted, in terms of the number of defects which are likely to be found. The screening and test facilities which the manufacturer has available for screening must be addressed in preparing the screening program plan and in the screen selection and placement process. Costs versus the benefits to be derived from screening should be addressed.

The criterion used in the handbook to judge cost effectiveness is the combined cost to the producer and customer. If the cost per defect eliminated is found to be higher than required or optimum, then the manufacturer should determine alternative methods which lower the costs of finding and eliminating the defects. Alternatives might include reducing the incoming defect density by means other than assembly screening, (e.g., increase the quality level of parts used) increase the screening strength at lower assembly levels, or eliminate screens which may be of questionable value. In those cases, where field reliability is an overriding requirement, then the Government procuring activity must decide on the appropriate cost-reliability trade-off.

The procedures contained in the handbook not only optimize the screen selection and placement but also provide management with tools and methodology to optimize resource allocations and to assess the cost trade-offs between defect prevention through analysis and corrective action, and screening.

5. DETAILED GUIDELINES

5.1 ESS Implementation Procedures. The following paragraphs outline the procedures required to design, implement, and monitor a factory ESS program with the objective of continuously reducing defects through preventive actions such that ESS can be reduced to a minimum (and ideally eliminated except for that portion required for PRVT). The procedures are aimed at optimizing the combined user/producer cost of achieving a required field reliability under prevailing conditions.

An ESS program consists of three phases - planning, development, and production.

The planning phase is used to (a) design a cost optimized factory ESS program that achieves the required field reliability for an existing design and defect density, and to (b) create a suite of quantitative factory requirements that are meaningfully related to the required reliability and are measurable and monitorable by the producer. The planning phase uses defect density and screening strength data provided in the handbook and industry and user's data. Since the data are approximations, the values must be validated and refined during the development phase.

During the development phase, monitor and control procedures are used to quantitatively measure fallout data and thus refine the estimates for defect density and screening strength so that appropriate modifications can be made for production. Similar procedures are used throughout the production phase to provide a quantitative assessment and feedback on whether or not reliability requirements are being achieved and the extent that continuous improvement is being realized. If problems exist, the procedures assist in focusing on problem areas and/or identifying the areas requiring more in depth or root cause analysis. The methodology allows for a continual reduction in ESS/screening as defect densities are reduced through corrective action (provided customer reliability requirements are satisfied) and thus allows the user and producer to optimize the product cost and reliability. The procedures also provide management with the necessary visibility and models for assessing the tradeoffs between defect prevention and screening and assessing the return and effectiveness of resource allocations.

The ESS program includes a PRVT segment that is used in conjunction with ESS data analysis to provided the necessary confidence that field reliability will be achieved. The PRVT segment is calibrated during the development phase and is a fixed segment of the system level factory ESS. As defects are prevented through corrective action and ESS consequently reduced, the PRVT segment becomes useful in flagging possible out of control conditions that could otherwise be missed (due to the reduced ESS). The PRVT segment thus serves multi-purpose roles for ESS polishing, field reliability indication, and out of control identification.

It should be noted that software is available from RADC which fully automates these procedures.

There are a total of six procedures:

a. Procedure A entitled, "Optimizing Screen Selection and Placement" uses procedures B and C (which estimate defect density and screening strength respectively) to design the ESS program, and Procedure D to validate the original estimates of defect density and screening strength and refine the program.

b. Procedure B entitled, "Estimating Defect Density" is used to estimate the incoming defect density.

c. Procedure C entitled, "Estimating Screening Strength" is used to estimate the screening strength.

d. Procedure D entitled, "Refining Estimates of Defect Density and Screening Strength" is used to analyze factory fallout data to provide revised estimates of Din and SS.

e. Procedure E entitled, "Monitor and Control" is used to provide a quantitative assessment of whether reliability requirements are being attained and to what extent continuous improvement is being realized.

f. Procedure F entitled Product Reliability Verification Test (PRVT) is used in conjunction with Procedure E for Monitor and Control Purposes to provide confidence that field reliability will be achieved.

5.2 Procedure A - Optimizing Screen Selection and Placement.

5.2.1 Objective. To plan an ESS program such that the required field reliability is attained at an optimum combined user-producer cost.

5.2.2 Methodology. The field reliability is determined by the latent defects remaining at the time of shipment and the existence of non-screenable defects that result in a constant failure rate. The objective of this procedure is to optimize the cost of reducing the latent defect population to an acceptable level defined as that which achieves the required field reliability. In planning an ESS program the first step is to determine the maximum allowable remaining latent defects that allow the required reliability to be achieved. Having determined the maximum allowable remaining defects, the required factory screening strength is determined from the estimated initial defects (determined in Procedure B) by solving the equation:

$$SS = D_{REMOVED}/D_{INITIAL}$$

Knowing the required factory screening strength, the next step is to optimize the screen selection and placement based on the combined user-producer cost. This is accomplished by determining the cost of removing the required number of defects using various ESS options.

There are essentially three stages for applying this procedure. During the design stage initial estimates of Din and SS are derived using the mathematical modelling techniques of Appendix A and the data included in Procedures B and C augmented by any prior production history (collected and analyzed according to the techniques of

Procedure D) from similar equipment. A design safety margin is built in to account for accuracy limitations of the estimates. During the development and/or early production phase, additional ESS may be added to provide sufficient data to use the curve fitting technique of Procedure D to "calibrate" the factors determined in the design stage. A minimum of two RV cycles and 10 TC cycles are recommended. During the production phase the curve fitting techniques of Procedure D are used to refine and validate the program on a continual basis.

5.2.3 Procedure Steps.

Procedure A1. The objective of this procedure is to create the basic ESS model for a particular program and to determine the incoming defect density, allowable outgoing defect density, and factory ESS constraints.

Step 1. Determine the initial defects resident in each assembly at all test and integration levels using the methods of Procedure B. Proportion the defects into RV and TC sensitive populations using the ratio 20% RV, 80% TC (ref. 4.10.3.3) or other suitably determined ratio.

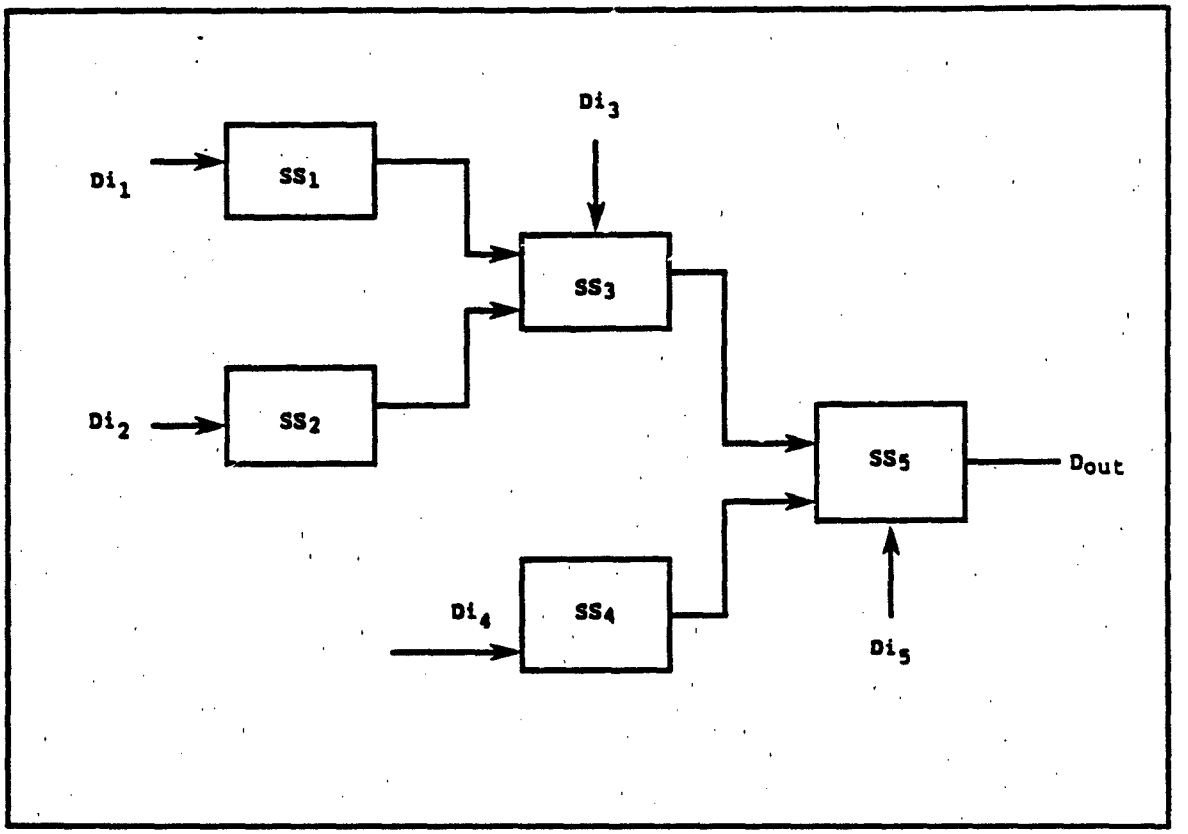
Step 2. Determine the factory integration sequence and define all restrictions and requirements with respect to assembly, calibration, and acceptance testing. For example, determine exactly when in the factory integration sequence any sub-assembly calibration procedure should be performed. Allow for final ATP and test over environment. Prepare a multi-level ESS flow diagram depicting the integration and environmental testing requirements as illustrated in Figure 5.1. This diagram illustrates the production flow and provides the framework for ESS selection and placement.

Step 3. Use Procedure C to determine the screening strength for various ESS options selected in Procedure A3. The model and calculations for a multilevel ESS flow are illustrated in Figure 5.1.

Step 4. Given the customer's reliability requirements, determine the maximum number of defects permissable at the time of shipment that allow this reliability to be achieved. This is a three stage process as follows:

a) Determine whether the equipment has a limiting MTBF. The limiting MTBF is the maximum that can be achieved and is limited by the state of the art in design, parts, materials, and processes and should be obtained from experience data from similar equipments.

b) Given the customer's required MTBF and using a suitable design safety margin to allow for estimation errors (typically 1.5 to 2) calculate the permissable failure rate (FR) due to latent defects using the expression



$$DOUT = Di_1 (1-SS_1)(1-SS_3)(1-SS_5) + Di_2 (1-SS_2)(1-SS_3)(1-SS_5) + Di_3 (1-SS_3)(1-SS_5) + Di_4 (1-SS_4)(1-SS_5) + Di_5 (1-SS_5)$$

Figure 5.1 Sample Multi Level ESS Flow Diagram

$$FR(\text{due to latent}) \leq \left(\frac{1}{\text{Required MTBF}} - \frac{1}{\text{Inherent MTBF}} \right) \times \frac{1}{\text{SAFETY MARGIN}}$$

c) To determine the maximum number of defects permissible at the time of shipment it is necessary to determine the relationship between failure rate and remaining defects $D_{REMAINING}$ as follows

$$① \; FR = \frac{DField(t)}{t}$$

where t is the period over which MTBF is to be measured and D_{Field} is the number of field failures due to latent defects occurring during the interval t.

② $D_{FIELD} = D_{REMAINING} \bullet SS_{FIELD}(t)$ where $SS_{FIELD}(t)$ is the equivalent screening strength of the field environment for a period t.

③ $SS_{FIELD}(t) = 1-\exp(-kt)$ where k is the field precipitation rate

Substituting (2) and (3) into (1) gives

$$FR = D_{REMAINING}\ (field\ stress)\ \frac{[1-exp(-kt]}{t}$$

In this expression $D_{REMAINING}$ (the number of defects remaining after factory screening), t and k are all defined with respect to the field stress. It is thus necessary to modify this expression by the stress adjustment factor (SAF) determined in Procedure B to determine the remaining defects at factory stress.

$$FR = D_{REMAINING} \bullet SAF\ \frac{[1-\exp(-kt]}{t}$$

This expression is applicable to both the RV and TC sensitive defect populations, therefore, the complete expression is:

$$FR = \frac{D_{REMAINING}(RV) \bullet SAF\,[1-\exp(-K(RV)t)] + D_{REMAINING}(TC) \bullet SAF\,[1-\exp(-K(TC)t)]}{t}$$

There are two methods for determining the value of k.

(i) If the field application environmental stresses are known, calculate k using the expressions given in step 1 of Procedure C.
(ii) If the field application stresses are not known, a suitable average value (based on industry or historical data) can be used. Typical values for K are 1/500 to 1/2000).

Step 5. Include the field model and parameters in the test flow diagram created in step 3 to complete the ESS Model. Figure 5.2 illustrates a portion of a sample ESS test flow diagram.

Procedure A2. The objective of this procedure is to determine the cost of the ESS program, defined as follows:

ESS COST = FACTORY TEST COST + FACTORY ESS COST + FACTORY REWORK COST + FIELD FAILURE COST.

Step 1. Determine the cost of factory testing. This should include all equipment costs including equipment calibration and maintenance, operation,

documentation, facilities, utilities (power, water, liquid nitrogen etc.) and labour costs including those associated with performing the screen, recording results, and performing quality assurance and administrative tasks.

Step 2. Determine the cost of factory ESS at each stage that it is performed. Include those factors and incidental costs mentioned in step 1.

Step 3. Determine the number of defects removed at each stage of screening using $D_{REMOVED} = DIN * SS$ (ref Appendix A). This is applicable to RV and TC separately. The RV and TC faults are also shown on the test flow diagram (ref. Figure 5.2).

Step 4. Determine the average total cost to repair defects at each stage. This cost will include all fault diagnostics, rework/repair, retest, repeat ESS, and data recording costs. Include all the incidental costs incurred. These should include carrying costs for spares, additional transit time for equipment, idle time, support and administration. Also included in these incidental costs should be logistics support considerations such as the costs associated with providing spares with a minimum amount of ESS.

Step 5. Determine the "defect cost" by multiplying the number of defects removed at each stage by the cost to repair each defect.

Step 6. Consider the user cost by treating the field as an extension of the ESS test flow and determining the user's cost due to a defect.

Step 7. Determine the total user/producer cost for the ESS program as the sum of those costs determined in steps 1 through 6.

Procedure A3. The objective of this procedure is to optimize the combined user/producer cost of achieving the specified reliability as calculated using Procedure A2. This is accomplished by selecting and placing RV and TC screens (with their respective strengths determined according to the methods of Procedure C) at various locations in the ESS model created in Procedure A1 and calculating the associated cost using Procedure A2. These costs and defects removed and remaining can be charted as illustrated in Figure 5.2.

Step 1. Selecting Assembly Level ESS. Usually ESS at the lowest level, i.e., part or assembly minimizes cost; however, depending on detection efficiency and the peculiarities of any particular electronic system, this may not always be the case. Use Table 4.9 as a guide in selecting the initial assembly level ESS.

Step 2. Select system level SS as required to achieve the desired field reliability. Use Table 4.9 as a guide. Note that at system level RV should always be followed by TC to enhance the detection efficiency.

Step 3. Determine the cost of this ESS plan using Procedure A2.

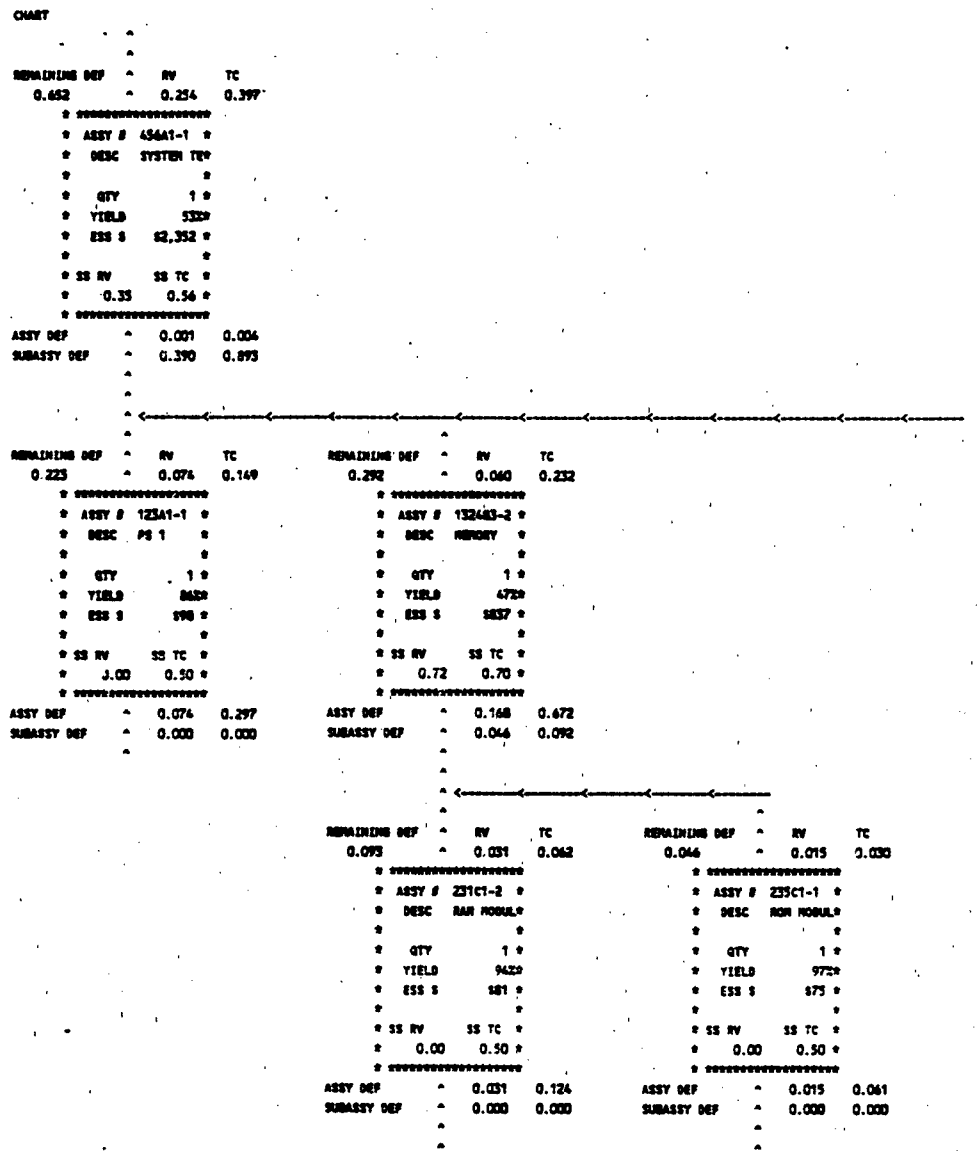


Figure 5.2 Sample ESS Test Flow Diagram

Step 4. Identify assemblies and modules with high system level ESS cost and for those specific assemblies select specific lower level (sub-assembly or part level) ESS. Reduce the system level SS as a result of making these changes ensuring that field reliability is achieved. Recalculate the ESS cost.

Step 5. Repeat step 4 until the program has been optimized for cost.

Procedure A4 After optimizing the screen selection and placement, it is necessary to ensure that the ESS is not having deleterious effects on the useful fatigue life. This is determined by calculating the damage index D from the equation $D = NS^B$ where N represents the stress duration, S = stress level, and B = fatigue exponent.

For TC_1 N = number of cycles
S = temperature range in degree Celsius
B = 2.5 (thermal fatigue exponent for solder)

For RV1 N = duration of vibration (hours or minutes)
S = Grms vibration level
B = 6.4 (vibration fatigue exponent for solder)

1 REF Crandall - Random vibration, publisher - John Wiley and Sons, NY
Engelmaier - Effects of Power Cycling in LCC; Bell Laboratories, NJ

Procedure A5. Refine the program as designed using A1 through A4 by determining actual values for Din, DE, PE, and SAF from factory and field data analyzed using Procedure D. The development or early preproduction phase should be used to verify and/or refine these original estimates. Subsequently, the production data should be analyzed on a regular basis to ensure the program remains optimum under changing conditions.

5.3 Procedure B - Estimating defect density.

5.3.1 Objective. Obtain estimates of the number of defects resident in the system prior to beginning ESS.

5.3.2 Methodology. Various imperfections are introduced during the assembly and integration of the equipment due to state of the art limitations in the design, testing, and manufacturing of parts and assemblies. The total number of imperfections is dependent upon these factors; the quantity and quality (technology, screening, reliability level, etc.) of the parts used and the assembly complexity (number of connections, processing, packaging densities, etc.) Unless removed through factory ESS some fraction of these imperfections will precipitate under field stress conditions and cause equipment failure. The number of imperfections that will precipitate is dependent upon the factors mentioned above and the field stress levels. The number of defects for either factory ESS or field must therefore be defined relative to the applicable factory and field stress levels.

In this procedure the number of defects is defined relative to a baseline stress level equivalent to R&M 2000 ESS guidelines. Appropriate factors are then applied

to determine the number of defects for different stress levels of vibration, temperature and temperature transition rates that occur in the factory and field. It is important to address the stress adjustment factors when planning an ESS program since they affect the economic optimization. Increasing ESS stress levels causes more defects to precipitate (than would normally occur in the field), incurring added rework and retest cost. Reducing ESS stress levels increases the time required to remove field defects thereby affecting throughput and equipment utilization, etc. Note that factory ESS stress levels should always be higher than the application stresses.

To ensure that the ESS program has an appropriate balance of RV and T/C stresses, the estimated defects must be divided in groups.

- RV defects (i.e., those defects that can be precipitated by RV stress only)
- T/C defects (i.e., those defects that can be precipitated by T/C stress only)
- RV-T/C defects, (i.e. those defects that can be precipitated by either T/C or RV stress)
- Time-Temperature - Humidity - Bias (TTHB) defects, (i.e., those defects precipitated by a combination of time, temperature, humidity, and electrical bias)
- Mechanical Shock (MS), (i.e., those defects precipitated by mechanical shock).

Factory ESS is effective in removing RV, MS, and T/C sensitive defects with the majority of TTHB sensitive defects escaping to the field. Field defects thus comprise residual RV and T/C defects approaching a constant failure rate distribution (i.e., the screening limit). TTHB defects have a different time to failure distribution than T/C or RV defects and for practical purposes are considered non-screenable and are not addressed by this ESS program.

The procedure steps are as follows:

i) Estimate defects for each assembly and the total system at base line stress.

ii) Proportion the defects into RV and T/C sensitive populations.

iii) Apply stress adjustment factors to determine the defects under different factory stress levels.

The initial estimates derived using these procedures are only approximate and should be refined based on the user's actual data obtained during the development phase or from the production of similar equipment. Adjustment may be required on a system or individual assembly basis. The procedures for refining the original estimate are provided in Procedure D.

5.3.3 Procedure steps.

Procedure B1 Determine the number of latent defects resident in the equipment at baseline stress as follows:

Step 1. The number of defects in a system depends on the quantity and quality of parts and workmanship characteristics. Therefore it is first necessary to determine the system complexity which is described by a complexity matrix. This matrix comprises the individual complexity vectors for each assembly and sub-assembly, including appropriate factors for multi-use assemblies. These complexity vectors are defined by the quantity of parts used in various part-type reliability categories and the quantity of manufacturing (assembly and soldering) characteristics present as defined in MIL-STD-2000. A sample assembly complexity vector is shown in Figure 5.3.

Step 2. Determine the initial number of defects at baseline stress by multiplying the system complexity matrix by the baseline stress defect density vector. The baseline stress defect density vector is determined from Table 5.1 or from prior industry and user data. A sample system defect density breakdown is shown in Figure 5.4.

Step 3. Proportion the total defects into populations that are sensitive to RV and TC. This improves the modelling accuracy and ensures a suitable balance of RV and TC is achieved. Studies indicate that typically 20% of the total defects are sensitive to RV and 80% to TC (reference 4.10.3.3).

NOTE: The population of RV and TC defects is based on the total population and not the factory fallout. Some factory fallout is affected by the relative RV and TC screening strengths.

ASSY NO	149C3-3	QTY/Nxt ASY	1			SCREEN #	1	
DESCRIPTION	PWR SUPPLY	RV DE	0.5			TC DE	0.5	
USED ON	456A1-1	TEST $	$50			REWORK $	$100	
PART/GRADE	S	B	B0	B1	C	C1	D	
MICROCCTS	0	35	0	61	0	0	0	
	S	TXV	TX	JAN	LWR	MISC	Plast	
TRANSISTORS	0	46	0	15	0	0	0	
DIODES	0	120	0	22	0	0	0	
	S	R	P	M	L	MIL	LWR	
RESISTORS	0	0	277	0	0	3	0	
CAPACITORS	0	0	118	0	0	14	0	
	MIL	LWR		MIL	LWR		ALL	
MAGNETICS	0	12	RELAYS	3	0	ROTATE	0	
CONNECTOR	5	0	SWITCH	0	0	MISC 1	0	
			PWB	1	0	MISC 2	0	
CONNECTIONS	PTH	PINS	LEADS	SOLDER#	ASSY#		TOT PARTS	
	568	96	2806	2806	3544		738	

Figure 5.3 Sample Assembly Complexity Vector

Table 5.1 Baseline Stress Defect Density Vectors (ppm)

MICROELECTRONICS DEVICES								
S	B	B-0	B-1	B-2	C	C-1	D	D-1
104.85	209.7	419.25	628.95	1362.6	1677	2725.2	3668.55	7336.9

TRANSISTORS					RELAYS		SWITCHES	
B/TXV	BO/TX	B1/JAN	C/LOWER	D/PLASTIC	MIL	LOWER	MIL	LOWER
312.3	624.6	3123	15615	31229.85	7307.4	21662.1	62.25	1119.3

DIODES						ROTATING DEVICES	CONNECTORS	
S	B/TXV	BO/TX	B1/JAN	C/LOWER	D/PLASTIC	ALL	MIL	LOWER
12.9	64.2	128.55	642.75	3213.45	6428.9	124561.8	2089.65	4139.4

RESISTORS						PWB	
S	R	P	M	MIL	LOWER	MIL	LOWER
8.1	26.85	80.7	269.25	1346.1	4038.3	9209.4	92094.45

CAPACITORS							MAGNETICS	
S	R	P	M	L	MIL	LOWER	MIL	LOWER
12.45	41.52	124.53	415.11	1245.36	1245.36	4151.25	1693.02	5643.45

ASSEMBLY CHARACTERISTICS	SOLDER CHARACTERISTICS
ALL	ALL
25	5

EQUIPMNT	EXAMPLE ASSY DEF	1.124	PART DEF	0.806	WRK DEF	0.318	
ENVIRON	aif	ESS $	$1,000	DEF REMVD	0.000	DEF REMN	1.1236

PART/GRADE	S	B/TXV	BQ/TX	B1/JAN	C/LWR	C1/MISC	D/Plast
MICROCCTS	0	284	0	261	0	0	0
TRANSISTORS	0	174	0	118	0	0	0
DIODES	0	374	0	40	0	0	0

	S	R	P	M	L	MIL	LWP
RESISTORS	0	0	1265	0	0	31	0
CAPACITORS	0	0	696	0	0	24	0

	MIL	LWR		MIL	LWR		ALL
MAGNETICS	5	17	RELAYS	12	0	ROTATE	0
CONNECTOR	31	0	SWITCH	0	0	MISC 1	0
			PWB	7	0	MISC 2	0

P.T. HOLE	9113	LEADS	14124	PARTS	3370	
PINS	1973					
ASSY #	17494	SOLDER #	25212	TOTAL WRK	42706	

Figure 5.4 Sample System Defect Density Breakdown

Procedure B2 Determine the stress adjustment factor relating defects at factory (baseline stress) levels to defects at the field application stress levels as follows:

Step 1. Use tables 5.2 through 5.13 to determine the defect density vector at the anticipated field stress level. These tables represent the defect density for different application environments and were derived from field data. For factory ESS planning purposes, these tables should be rescaled to also include the defects removed by factory screening. A factor of 1.5 is typical. Multiply the system complexity matrix from Procedure B1 step 1 by the field stress defect density vector to determine the initial number of defects at the anticipated field stress levels.

Step 2. Determine the field stress adjustment factor as the ratio of the number of defects at the field stress level to the number of defects at the baseline stress level (from Procedure B1).

Step 3. If factory stress levels do not conform to the base line stress levels (defined as 6 Grms and 4 degrees C/min) apply a suitable factory stress adjustment factor (SAF) as follows:

$$For\ RV\ \ SAF = \left(\frac{actual\ Grms}{6\ Grms}\right)^{n} \quad n\ typically\ 0.5\ to\ 1.0$$

$$For\ TC\ \ SAF = \left(\frac{actual\ transition\ rate}{4\ degrees\ C/min}\right)^{n} \quad n\ typically\ 0\ to\ .5$$

5.4 Procedure C - Estimating Screening Strength

5.4.1 Objective. Estimate the number of flaws precipitated and detected (removed) by ESS.

5.4.2 Methodology. The screening strength is characterized by a precipitation term and a detection term and determines the fraction of existing flaws that are removed by ESS. The precipitation and detection terms are estimated separately and it is their product that determines the screening strength.

Precipitation is defined as the conversion of flaws with some residual strength (latent defect) into a flaw with no strength (patent defect)- for example the propagation of a crack through a wire until the wire is broken. The application of stress precipitates a certain fraction of the existing flaws. This fraction is assumed to be constant for a specified stress level and duration and the mathematics are discussed in more detail in Appendix A. A previous study ref. RADC-TR-86-149 has determined the precipitation effectiveness of various stress types and has developed mathematical expressions for each. These expressions and representative tables are provided in Tables 5.14 to 5.17. As in the estimation of initial defects, the original estimate based on these tables is only approximate and must be validated or refined based on actual user's data.

Table 5.2 Microelectronic Devices Defect Density (in PPM) for various Environments

Environment	Quality Level								
	S	B	B-0	B-1	B-2	C	C-1	D	D-1
GB	9.2	18.3	36.6	54.9	119.0	146.4	237.9	320.3	640.6
GF	19.4	38.7	77.4	116.1	251.6	309.6	503.2	677.3	1354.6
GM	27.5	55.1	110.1	165.2	357.9	440.5	715.8	963.6	1927.2
NP	25.6	51.2	102.4	153.6	332.9	409.7	665.8	896.3	1792.5
NSB	26.6	53.1	106.3	159.4	345.4	425.1	690.8	929.9	1859.9
NS	26.6	53.1	106.3	159.4	345.4	425.1	690.8	929.9	1859.9
NU	34.7	69.5	139.0	208.5	451.7	556.0	903.5	1216.2	2432.5
NH	35.7	71.4	142.8	214.3	464.3	571.4	928.5	1249.9	2499.9
NUU	37.6	75.3	150.5	225.8	489.3	602.2	978.6	1317.3	2634.6
ARW	48.2	96.4	192.9	289.3	626.9	771.6	1253.8	1687.8	3375.6
AIC	19.4	38.7	77.4	116.1	251.6	309.6	503.2	677.3	1354.6
AIT	21.8	43.5	87.0	130.5	282.9	348.1	565.7	761.5	1523.1
AIB	31.4	62.8	125.5	188.3	408.0	502.1	815.9	1098.4	2196.7
AIA	26.6	53.1	106.3	159.4	345.4	425.1	690.8	929.9	1859.9
AIF	36.2	72.4	144.8	217.2	470.5	579.1	941.0	1266.8	2533.5
AUC	21.8	43.5	87.0	130.5	282.9	348.1	565.7	761.5	1523.1
AUT	26.6	53.1	106.3	159.4	345.4	425.1	690.8	929.9	1859.9
AUB	43.4	86.8	173.6	260.5	564.3	694.6	1127.7	1519.4	3038.8
AUA	36.2	72.4	144.8	217.2	470.5	579.1	941.0	1266.8	2533.5
AUF	50.6	101.3	202.5	303.8	658.2	810.1	1316.4	1772.0	3544.0
SF	11.7	23.3	46.6	69.9	151.5	186.4	303.0	407.9	815.7
MFF	26.1	52.2	104.4	156.5	339.2	417.4	678.3	913.1	1826.2
MFA	33.3	66.6	133.2	199.8	433.0	532.9	866.0	1165.7	2331.4
USL	60.3	120.5	241.0	361.5	783.3	964.0	1566.6	2108.8	4217.7
ML	69.9	139.8	279.5	419.3	908.4	1118.0	1816.8	2445.7	4891.3
CL	1065.9	2131.8	4263.7	6395.5	13857.0	17054.8	27714.0	37307.4	74614.7

Table 5.3 Transistor Devices Defect Density (in PPM) for various Environments

	Quality Level				
Environment	JANTXV	JANTX	JAN	Lower	Plastic
GB	10.9	21.9	109.3	546.6	1093.2
GF	34.6	69.2	346.0	1730.2	3460.4
GM	98.8	189.5	947.7	4738.5	9477.0
MP	65.2	130.4	651.8	3259.0	6518.0
NSB	54.3	108.7	543.3	2716.5	5433.1
NS	54.3	108.7	543.3	2716.5	5433.1
NU	109.6	219.1	1095.7	5478.3	10956.6
NH	99.7	199.4	997.0	4985.1	9970.2
NUU	104.6	209.3	1046.3	5231.7	10463.4
ARW	139.2	278.3	1391.6	6957.8	13915.6
AIC	52.9	105.7	528.5	2642.6	5285.1
AIT	80.0	160.0	799.8	3998.8	7997.5
AIB	178.6	357.2	1786.1	8930.5	17860.9
AIA	104.6	209.3	1046.3	5231.7	10463.4
AIF	203.3	406.5	2032.7	10163.4	20326.8
AUC	80.0	160.0	799.8	3998.8	7997.5
AUT	129.3	258.6	1292.9	6464.6	12929.2
AUB	301.9	603.8	3019.0	15095.1	30190.1
AUA	178.6	357.2	1786.1	8930.5	17860.9
AUF	326.6	653.1	3265.6	16328.0	32656.0
SF	8.0	15.9	79.7	398.6	797.3
MFF	65.2	130.4	651.8	3259.0	6518.0
MFA	89.8	179.7	898.4	4491.9	8983.9
USL	183.5	367.1	1835.4	9177.0	18354.1
ML	208.2	416.4	2082.0	10410.0	20819.9
CL	3408.9	6817.7	34088.7	170443.3	340886.7

Table 5.4 Diode Part Devices Defect Density (in PPM) for various Environments

	Quality Level					
Environment	JANS	JANTXV	JANTX	JAN	Lower	Plastic
GB	1.2	5.9	11.8	59.2	296.2	592.3
GF	1.7	8.6	17.2	86.0	430.0	860.0
GM	4.3	21.6	43.2	216.2	1080.8	2161.5
MP	3.2	16.1	32.2	160.8	803.8	1607.7
NSB	1.9	9.4	18.9	94.2	471.5	943.1
NS	1.9	9.4	18.9	94.3	471.5	943.1
NU	4.9	24.4	48.8	243.8	1219.2	2438.5
NH	4.5	22.5	45.1	225.4	1126.9	2253.8
NUU	4.7	23.5	46.9	234.6	1173.1	2346.2
ARW	6.0	29.9	59.8	299.2	1496.2	2992.3
AIC	3.8	18.8	37.7	188.5	942.3	1884.6
AIT	4.7	23.5	46.9	234.6	1173.1	2346.2
AIB	6.5	32.7	65.4	326.9	1634.6	3269.2
AIA	5.6	28.1	56.2	280.8	1403.8	2807.7
AIF	7.5	37.3	74.6	373.1	1865.4	3730.8
AUC	5.6	28.1	56.2	280.8	1403.8	2807.7
AUT	6.5	32.7	65.4	326.9	1634.6	3269.2
AUB	10.2	51.2	102.3	511.5	2557.7	5115.4
AUA	8.4	41.9	83.8	419.2	2096.2	4192.3
AUF	10.2	51.2	102.3	511.5	2557.7	5115.4
SF	1.2	5.9	11.8	59.2	296.2	592.3
MFF	3.2	16.1	32.2	160.8	803.8	1607.7
MFA	4.1	20.7	41.4	206.9	1034.6	2069.2
USL	7.6	38.2	76.5	382.3	1911.5	3823.1
ML	8.6	42.8	85.7	428.5	2142.3	4284.6
CL	128.4	641.9	1283.8	6419.2	32096.2	64192.3

Table 5.5 Resistor Devices Defect Density (in PPM) for various Environments

	Quality Level					
Environment	S	R	P	M	MIL-SPEC	Lower
GB	0.4	1.2	3.7	12.3	61.4	184.2
GF	0.6	2.0	6.1	20.3	101.7	305.2
GM	1.5	5.1	15.4	51.5	257.4	772.3
MP	1.7	5.7	17.2	57.2	286.2	858.7
NSB	0.9	3.1	9.2	30.7	153.6	460.9
NS	1.0	3.4	10.1	33.6	168.1	504.2
NU	2.6	8.7	26.2	87.2	436.2	1308.5
NH	2.6	8.7	26.2	87.2	436.2	1308.5
NUU	2.8	9.3	27.9	93.0	465.0	1395.0
ARW	3.5	11.6	34.8	116.1	580.3	1740.9
AIC	0.6	2.1	6.3	20.9	104.6	313.9
AIT	0.7	2.4	7.1	23.8	119.0	357.1
AIB	1.3	4.4	13.2	44.0	219.9	659.8
AIA	1.2	4.1	12.3	41.1	205.5	616.6
AIF	1.8	5.8	17.5	58.4	292.0	876.0
AUC	1.4	4.7	14.1	46.9	234.4	703.1
AUT	1.3	4.4	13.2	44.0	219.9	659.8
AUB	2.8	9.3	27.9	93.0	465.0	1395.0
AUA	2.8	9.3	27.9	93.0	465.0	1395.0
AUF	3.7	12.2	36.5	121.8	609.1	1827.4
SF	0.3	0.9	2.6	8.8	44.1	132.3
MFF	1.7	5.8	17.3	57.8	289.1	867.4
MFA	2.3	7.6	22.7	75.7	378.5	1135.5
USL	4.7	15.6	46.9	156.4	782.1	2346.3
ML	5.4	17.9	53.8	179.5	897.4	2692.2
CL	88.4	294.7	884.1	2947.0	14735.0	44205.0

Table 5.6 Capacitor Defect Density (in PPM) for various Environments

Environment	Quality Level						
	S	R	P	M	L	MIL-SPEC	Lower
GB	1.2	3.8	11.5	38.4	115.3	115.3	384.4
GF	1.8	6.2	18.4	61.5	184.5	184.5	615.0
GM	9.0	30.0	89.9	299.8	899.4	899.4	2998.1
MP	12.7	42.3	126.8	422.8	1268.4	1268.4	4228.1
NSB	5.8	19.2	57.7	192.2	576.6	576.6	1921.9
NS	6.3	21.1	63.4	211.4	634.2	634.2	2114.1
NU	14.3	47.7	143.0	476.6	1429.9	1429.9	4766.2
NH	18.4	61.5	184.5	615.0	1845.0	1845.0	6150.0
NUU	20.8	69.2	207.6	691.9	2075.6	2075.6	6918.7
ARW	27.7	92.2	276.7	922.5	2767.5	2767.5	9225.0
AIC	3.5	11.5	34.6	115.3	345.9	345.9	1153.1
AIT	3.5	11.5	34.6	115.3	345.9	345.9	1153.1
AIB	5.8	19.2	57.7	192.2	576.6	576.6	1921.9
AIA	3.5	11.5	34.6	115.3	345.9	345.9	1153.1
AIF	6.9	23.1	69.2	230.6	691.9	691.9	2306.2
AUC	8.6	28.8	86.5	288.3	864.8	864.8	2882.8
AUT	9.2	30.7	92.2	307.5	922.5	922.5	3075.0
AUB	11.5	38.4	115.3	384.4	1153.1	1153.1	3843.7
AUA	9.2	30.7	92.2	307.5	922.5	922.5	3075.0
AUF	17.3	57.7	173.0	576.6	1729.7	1729.7	5765.6
SF	0.9	3.1	9.2	30.7	92.2	92.2	307.5
MFF	12.7	42.3	126.8	422.8	1268.4	1268.4	4228.1
MFA	17.3	57.7	173.0	576.6	1729.7	1729.7	5765.6
USL	36.9	123.0	369.0	1230.0	3690.0	3690.0	12300.0
ML	41.5	138.4	415.1	1383.7	4151.2	4151.2	13837.5
CL	703.4	2344.7	7034.1	23446.9	70340.6	70340.6	234468.6

Table 5.7 Magnetic Defect Density (in PPM) for various Environments

	Quality Level	
Environment	MIL-SPEC	Lower
GB	537.2	1790.7
GF	1222.9	4076.4
GM	1996.1	7140.1
MP	2142.0	6653.8
NSB	1135.4	3784.6
NS	1222.9	4076.4
NU	2433.8	8112.7
NH	2725.6	9085.3
NUU	3017.4	10058.0
ARW	3892.7	12975.8
AIC	1047.8	3492.8
AIT	1266.7	4222.3
AIB	1266.7	4222.3
AIA	1266.7	4222.3
AIF	1704.4	5681.2
AUC	1339.6	4465.4
AUT	1339.6	4465.4
AUB	1485.5	4951.7
AUA	1485.5	4951.7
AUF	1850.3	6167.5
SF	537.2	1790.7
MFF	1996.1	6653.8
MFA	2579.7	8599.0
USL	5059.9	16866.2
ML	5643.4	18811.5
CL	89385.3	297951.1

Precipitation by itself does not ensure that flaws can be detected. In many instances a concurrent stress may be required to detect and isolate the failure. For example, a broken wire may make intermittent contact at low, ambient stresses. Also, depending upon the function affected, the defect may only cause degraded performance. Either condition could require extended testing and may require concurrent stress. The capability of detecting a patent defect is measured by the detection efficiency.

The removal of a potential defect or flaw requires the flaw to be precipitated and subsequently detected and removed. The detection efficiency is defined as the capability of detecting, isolating and removing the defect once it has precipitated. It is a measure of the extent that factory testing exercises all possible field applications and conditions and is the product of the following factors and considerations:

(a) Probability of observing functional and parametric defects (i.e., probability of detection x probability of occurrence)

(b) Necessity for concurrent stress

(c) Probability of isolating and then removing the defect without creating an additional defect(s)

Studies indicate that a large fraction of defects require concurrent stress to be detectable. Therefore ESS that does not employ testing during stress application is relatively ineffective. It is also the reason that RV stress should be followed by T/C. RV is relatively short in duration, thus the detection efficiency, which has a Poisson $(1 - e^{-kt})$ distribution may be inadequate.

5.4.3 Procedure Steps

Step 1. Determine the precipitation efficiency. Expressed as a function of stress duration, the precipitation efficiency is given by 1-exp (-kt) where t is the stress duration in hours, cycles, etc and k is a stress constant determined for each type of stress according to the following formulae:

Temperature Cycling $k = 0.0017\ (\Delta T + .6)^{.6}\ [\ln(RATE + 2.718)]^3$ where

$\Delta T = T_{max} - T_{min}$ in degrees C and RATE = degrees C/minute

Constant Temperature $k = 0.0017\ (T + .6)^{.6} t$ where T = degrees C, and t = hours

Random Vibration $k = 0.0046\ G^{1.71}$

Swept Sine Vibration $k = 0.000727 G^{0.863}$ G in Grms

Fixed Sine Vibration $k = 0.00047\ G^{0.49}$

Tables 5.14 to 5.17 provide examples of precipitation efficiency for various screening parameters. For RV screens it is necessary to include an axis sensitivity factor. RV applied in the axis perpendicular to the plane of the board will have the greatest effect. When selecting and modelling RV stress, the

precipitation efficiency is thus given by [1 - exp (-kt)]* AXIS SENSITIVITY FACTOR where the axis sensitivity factor is the defect density component in the sensitive axis divided by the total defect density. Transmisibility and resonance effects must be considered and the frequency spectrum may need to be suitably notched to avert overstress or wear-out effects. Similarly thermal mass and conductivities must be considered when determining TC transition rates and required dwell times. The stress levels for all these equations pertain to the equipment being screened and not the chambers etc.

It should also be noted that the expressions and tables for precipitation efficiency are only approximate and, as in the estimation of initial defects, should be refined based upon actual users data according to the techniques of Procedure D.

Step 2. Determine the detection efficiency (DE) The DE term is sensitive to three factors and must be estimated accordingly. These three factors (and their respective range of values) are:

a) Type of testing performed:

Functional only	0.5 to 0.8
Functional and parametric	0.8 to 1.0

b) Environmental conditions during test:

Testing performed under ambient conditions only	0.2 to 0.6
Testing performed concurrently with stress	1.0

c) The ability to observe and isolate the defect and the probability of successfully removing the defect without introducing another 0.8 to 1.0

The product of these factors is the detection efficiency.

Step 3. Determine the screening strength as the product of the precipitation efficiency and detection efficiency.

EXAMPLE OF SS CALCULATION

For TC of 4 cycles at 5°C/minute over a 100°C range, PE = .6027 (from Table 5.15)

For RV of 5 minutes at 5Grms, PE = .303 (from Table 5.16)

Given the following "DE" factors

functional and parametric Test	.9
Test during environmental stress	1
Probability of detecting, isolating and removing the defect	.95

The detection efficiency is 0.9 x 1.0 x .95 = .855

SS (TC) = PE x DE = .6027 * .855 = 0.5153

SS (RV) = PE x DE = .303 * .855 = 0.259

Table 5.8. Rotating Devices Defect Density (in PPM) for various Environments

Environment	Fraction defective (Defects/10^6)
GB	5935.2
GF	11663.1
GM	30168.5
NP	27965.5
NSB	14967.6
NS	16289.4
NU	34574.6
NH	38980.6
NUU	43386.7
ARW	56604.8
AIC	12544.3
AIT	13645.8
AIB	15848.8
AIA	13645.8
AIF	23559.4
AUC	14747.3
AUT	18051.9
AUB	20254.9
AUA	18051.9
AUF	25762.5
SF	5935.2
MFF	27965.5
USL	74229.1
ML	83041.2
CL	-------

Table 5.9. Relay Defect Density (in PPH) for various Environments

Environment	Quality Level	
	MIL-SPEC	Lower
GB	142.5	210.9
GF	231.4	388.8
GM	635.1	1784.5
MP	1510.8	4384.3
NSB	621.4	1716.0
NS	621.4	1716.0
NU	1031.9	2673.9
NH	2263.4	6642.0
NUU	2400.2	6915.7
ARW	3221.2	9652.3
AIC	460.1	724.0
AIT	484.5	1100.3
AIB	758.2	1442.4
AIA	587.2	1100.3
AIF	758.2	1784.5
AUC	621.4	1442.4
AUT	689.8	1784.5
AUB	1100.3	2810.7
AUA	758.2	2126.5
AUF	1100.3	3152.8
SF	142.5	210.9
MFF	1510.8	4384.3
MFA	2058.1	5684.2
USL	4315.8	13073.1
ML	4931.6	14441.4
CL	N/A	N/A

Table 5.10. Switch Defect Density (in PPM) for various Environments

	Quality Level	
Environment	MIL-SPEC	Lower
GB	1.4	24.4
GF	2.4	44.0
GM	8.8	158.4
MP	12.8	230.6
NSB	5.3	95.3
NS	5.3	95.5
M'	12.2	220.3
MN	19.1	344.1
NUU	20.3	364.7
ARW	27.1	488.4
AIC	5.4	96.6
AIT	5.4	96.6
AIH	9.4	168.8
AIA	9.4	168.8
AIF	12.2	220.3
AUC	6.5	117.2
AUT	6.5	117.2
AUB	12.2	220.3
AUA	12.2	220.3
AUF	15.1	271.9
SF	1.4	24.4
MFF	12.8	230.6
MFA	17.4	313.1
USL	36.9	663.7
ML	41.5	746.2
CL	688.3	12388.6

Table 5.11. Connector Defect Density (in PPM) for various Environments

	Quality Level	
Environment	MIL-SPEC	Lower
GB	73.7	97.3
GF	83.2	248.1
GR	417.7	1204.6
MP	427.1	827.7
MSB	219.8	408.3
MS	276.3	544.9
MU	639.2	1298.9
MM	639.2	1251.8
MUU	686.3	1346.0
ARW	921.9	1770.1
AIC	120.5	497.8
AIT	168.0	497.8
AIB	238.7	733.4
AIA	215.1	733.4
AIF	332.9	969.0
AUC	262.2	733.4
AUT	403.6	733.4
AUB	497.8	969.0
AUA	474.3	969.0
AUF	733.4	1440.2
SF	73.7	97.3
NFF	427.1	827.7
NFA	592.1	1157.5
USL	1204.6	2382.7
ML	1393.1	2759.6
CL	23115.8	45733.8

Table 5.12. PWB Defect Density (in PPM) for various Environments

Environment	Quality Level	
	MIL-SPEC	Lower
GB	425.0	4250.0
GF	690.3	6903.2
GM	1792.4	17924.3
MP	1629.2	16291.5
NSB	1057.7	10576.9
NS	1302.6	13026.0
NU	2670.0	26700.3
NH	2874.1	28741.2
NUU	3078.2	30782.2
ARW	4098.7	40986.9
AIC	731.1	7311.4
AIT	1139.3	11393.2
AIB	1853.7	18536.5
AIA	1567.9	15679.2
AIF	2261.8	22618.4
AUC	1751.6	17516.1
AUT	3282.3	32823.1
AUB	5323.3	53232.5
AUA	4302.8	43027.8
AUF	7364.2	73641.9
SF	425.0	4250.0
MFF	1996.5	19965.2
MFA	2670.0	26700.3
USL	5527.3	55273.5
ML	6139.6	61396.3
CL	102267.9	-------

Table 5.13. Manufacturing Characteristics (in ppm) in Various Environments

ENVIRONMENT	MANUFACTURING CHARACTERISTICS	
	ASSEMBLY	SOLDER
GB	0.98	1.25
GF	0.98	1.25
GM	4.90	6.27
MP	4.90	6.27
NSB	1.96	2.51
NS	2.94	3.76
NU	6.86	8.78
NH	6.86	8.78
NUU	7.84	10.03
ARW	10.78	13.79
AIC	1.96	2.51
AIT	2.94	3.76
AIB	3.92	5.01
AIA	2.94	3.76
AIF	4.90	6.27
AUC	1.96	2.51
AUT	3.92	5.01
AUB	4.90	6.27
AUA	4.90	6.27
AUF	5.88	7.52
SF	0.98	1.25
MFF	4.90	6.27
MFA	6.86	8.78
USL	14.71	18.81
ML	16.67	21.31
CL	274.51	351.04

Table 5.14. Precipitation Efficiency Factors - Random Vibration Screens

Duration (minutes)	Acceleration Level (G-RMS)																		
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
5	0.007	0.023	0.045	0.072	0.104	0.140	0.178	0.218	0.260	0.301	0.346	0.389	0.431	0.471
10	0.014	0.045	0.088	0.140	0.198	0.260	0.324	0.389	0.452	0.514	0.572	0.627	0.677	0.723
15	0.021	0.067	0.129	0.202	0.282	0.363	0.444	0.522	0.595	0.661	0.720	0.772	0.816	0.854
20	0.028	0.088	0.168	0.260	0.356	0.452	0.543	0.626	0.700	0.764	0.817	0.861	0.896	0.923
25	0.035	0.109	0.206	0.314	0.424	0.529	0.625	0.708	0.778	0.835	0.880	0.915	0.941	0.959
30	0.041	0.129	0.241	0.363	0.484	0.595	0.691	0.772	0.836	0.885	0.922	0.948	0.966	0.979
35	0.048	0.149	0.275	0.409	0.538	0.651	0.746	0.822	0.878	0.920	0.949	0.968	0.981	0.988
40	0.055	0.168	0.308	0.452	0.586	0.700	0.791	0.860	0.910	0.944	0.966	0.981	0.989	0.994
45	0.061	0.187	0.339	0.492	0.629	0.742	0.829	0.891	0.933	0.961	0.978	0.988	0.994	0.997
50	0.068	0.205	0.369	0.529	0.668	0.778	0.859	0.915	0.951	0.973	0.986	0.993	0.996	0.998
55	0.074	0.224	0.397	0.563	0.702	0.809	0.884	0.933	0.964	0.981	0.991	0.996	0.998	0.999
60	0.081	0.241	0.424	0.595	0.734	0.836	0.905	0.948	0.973	0.987	0.994	0.997	0.999	1.000

Table 5.15. Precipitation Efficiency Factors - Temperature Cycling Screens

Number of Cycles	Temp Rate of Change °C/Min	Temperature Range R (°C)								
		20.	40.	60.	80.	100.	120.	140.	160.	180.
2	$\dot{T}$									
	5	.1633	.2349	.2886	.3324	.3697	.4023	.4312	.4572	.4809
	10	.2907	.4031	.4812	.5410	.5891	.6290	.6629	.6920	.7173
	15	.3911	.5254	.6124	.6752	.7232	.7612	.7920	.8175	.8388
	20	.4707	.6155	.7034	.7636	.8075	.8407	.8665	.8871	.9037
4	$\dot{T}$									
	5	.2998	.4147	.4939	.5543	.6027	.6427	.6765	.7054	.7305
	10	.4969	.6431	.7308	.7893	.8312	.8624	.8863	.9051	.9201
	15	.6292	.7748	.8498	.8945	.9234	.9430	.9567	.9667	.9740
	20	.7198	.8522	.9120	.9441	.9629	.9746	.9822	.9873	.9907
6	$\dot{T}$									
	5	.4141	.5522	.6400	.7025	.7496	.7864	.8160	.8401	.8601
	10	.6431	.7873	.8603	.9033	.9306	.9489	.9617	.9708	.9774
	15	.7742	.8931	.9418	.9657	.9788	.9864	.9910	.9939	.9958
	20	.8517	.9432	.9739	.9868	.9929	.9960	.9976	.9986	.9991
8	$\dot{T}$									
	5	.5098	.6574	.7439	.8014	.8422	.8723	.8953	.9132	.9274
	10	.7469	.8731	.9275	.9556	.9715	.9811	.9871	.9910	.9936
	15	.8625	.9493	.9774	.9889	.9941	.9967	.9981	.9989	.9993
	20	.9215	.9781	.9923	.9969	.9986	.9994	.9997	.9998	.9999
10	$\dot{T}$									
	5	.5898	.7379	.8178	.8674	.9005	.9237	.9405	.9529	.9623
	10	.8204	.9242	.9624	.9796	.9883	.9930	.9956	.9972	.9982
	15	.9163	.9759	.9913	.9964	.9984	.9992	.9996	.9998	.9999
	20	.9585	.9916	.9977	.9993	.9997	.9999	.9999	.9999	.9999
12	$\dot{T}$									
	5	.6568	.7994	.8704	.9115	.9373	.9544	.9661	.9744	.9804
	10	.8726	.9548	.9805	.9906	.9952	.9974	.9985	.9991	.9995
	15	.9490	.9886	.9966	.9988	.9996	.9998	.9999	.9999	.9999
	20	.9780	.9968	.9993	.9998	.9999	.9999	.9999	.9999	.9999

Table 5.16. Precipitation Efficiency Factors - Swept Sine Vibration Screens

Duration (minutes)	G Level														
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
5	0.0020	0.0036	0.0051	0.0066	0.0080	0.0093	0.0107	0.0120	0.0132	0.0145	0.0157	0.0169	0.0181	0.0193
10	0.0040	0.0072	0.0103	0.0131	0.0159	0.0186	0.0212	0.0238	0.0263	0.0287	0.0312	0.0335	0.0359	0.0382
15	0.0060	0.0108	0.0154	0.0196	0.0238	0.0278	0.0316	0.0354	0.0391	0.0428	0.0464	0.0499	0.0534	0.0568
20	0.0080	0.0144	0.0204	0.0261	0.0316	0.0368	0.0420	0.0470	0.0519	0.0566	0.0614	0.0660	0.0705	0.0750
25	0.0099	0.0180	0.0255	0.0325	0.0393	0.0458	0.0522	0.0584	0.0644	0.0703	0.0761	0.0818	0.0874	0.0929
30	0.0119	0.0216	0.0305	0.0389	0.0470	0.0547	0.0623	0.0696	0.0768	0.0838	0.0906	0.0973	0.1039	0.1104
35	0.0139	0.0251	0.0355	0.0452	0.0546	0.0636	0.0723	0.0807	0.0890	0.0970	0.1049	0.1126	0.1201	0.1275
40	0.0159	0.0287	0.0404	0.0515	0.0621	0.0723	0.0822	0.0917	0.1010	0.1101	0.1189	0.1276	0.1361	0.1444
45	0.0178	0.0322	0.0454	0.0578	0.0696	0.0810	0.0919	0.1026	0.1129	0.1230	0.1328	0.1424	0.1517	0.1609
50	0.0198	0.0357	0.0503	0.0640	0.0770	0.0895	0.1016	0.1133	0.1247	0.1357	0.1464	0.1569	0.1671	0.1771
55	0.0217	0.0392	0.0552	0.0701	0.0844	0.0980	0.1112	0.1239	0.1362	0.1482	0.1598	0.1711	0.1822	0.1930
60	0.0237	0.0427	0.0600	0.0763	0.0917	0.1065	0.1207	0.1344	0.1476	0.1605	0.1730	0.1852	0.1970	0.2085

Table 5.17. Precipitation Efficiency Factors - Constant Temperature Screens

Time in Hours	Temperature Delta (ΔT)								
	0.	10.	20.	30.	40.	50.	60.	70.	80.
10	0.0124	0.0677	0.0991	0.1240	0.1452	0.1639	0.1809	0.1964	0.2108
20	0.0247	0.1308	0.1885	0.2326	0.2693	0.3010	0.3290	0.3542	0.3772
30	0.0368	0.1896	0.2689	0.3278	0.3754	0.4156	0.4504	0.4810	0.5084
40	0.0488	0.2445	0.3414	0.4112	0.4661	0.5114	0.5498	0.5830	0.6121
50	0.0606	0.2956	0.4067	0.4842	0.5436	0.5915	0.6312	0.6649	0.6938
60	0.0723	0.3433	0.4655	0.5481	0.6099	0.6584	0.6979	0.7307	0.7584
70	0.0839	0.3877	0.5185	0.6042	0.6665	0.7144	0.7525	0.7836	0.8093
80	0.0953	0.4292	0.5663	0.6533	0.7149	0.7612	0.7973	0.8261	0.8495
90	0.1065	0.4678	0.6093	0.6963	0.7563	0.8004	0.8339	0.8602	0.8812
100	0.1176	0.5[illegible]	0.6480	0.7339	0.7917	0.8331	0.8640	0.8877	0.9063
110	0.1286	0.5374	0.6829	0.7669	0.8219	0.8605	0.8886	0.9097	0.9260
120	0.1394	0.5687	0.7144	0.7958	0.8478	0.8833	0.9087	0.9275	0.9416
130	0.1501	0.5979	0.7427	0.8211	0.8699	0.9025	0.9252	0.9417	0.9539
140	0.1607	0.6251	0.7682	0.8433	0.8888	0.9184	0.9388	0.9532	0.9636
150	0.1711	0.6505	0.7912	0.8628	0.9049	0.9318	0.9498	0.9624	0.9713
160	0.1814	0.6742	0.8119	0.8798	0.9187	0.9430	0.9589	0.9697	0.9774
170	0.1916	0.6962	0.8305	0.8947	0.9305	0.9523	0.9663	0.9757	0.9821
180	0.2017	.7168	0.8473	0.9077	0.9406	0.9602	0.9724	0.9805	0.9859
190	0.2116	0.7360	0.8625	0.9192	0.9492	0.9667	0.9774	0.9843	0.9889
200	0.2214	0.7538	0.8761	0.9292	0.9566	0.9721	0.9815	0.9874	0.9912

5.5 Procedure D - Refining Estimates of Defect Density and Screening Strength

5.5.1 Objective. To refine the estimates of ESS modelling parameters (D_{IN}, SS) using actual factory and field data.

5.5.2 Methodology. The most important parameter for ESS is the defects remaining at the time of shipment since this determines the field reliability. Other significant parameters are the initial defect density, and the screening strength of various screens. The difficulty however, is that none of these parameters are directly observable by the producer. Only the defects removed through factory ESS can be measured. This procedure provides the means for determining these other critical parameters from the factory data.

5.5.3 Procedure Steps.

Step 1. Collect the necessary factory (test and failure) data from a FRACAS system. When assembling this data it is imperative to distinguish between errors and defects. Errors are preventable and usually detectable without environmental stress. The primary concern of this procedure is the elimination of latent defects. The minimum data requirements for the FRACAS system are:

ESS Test Equipment
Stress Duration - ETI at start of test, completion of test, and time of failure
Test Type
Number of units tested - number that pass/fail
Assembly - Sub Assembly - part failed
Failure Cause

Step 2 To determine D_{IN}, PE, and $D_{REMAINING}$, curve fit the factory fallout data (determined in step 1) and field data to the following expression

$$Dfallout = DE\ [D_{PAT} + D_{LAT}\ [1-\exp(-kt)] + CFR.t]$$

The derivation of this expression is discussed in Appendix A and RADC technical report TBD and has been found to be adequately representative of the real world.

Collect the fallout data for each type of environment (i.e., temperature cycling, random vibration etc.) separately and prepare graphs with the cumulative defects, normalized as defects per system as the ordinate, and the stress duration as the abscissa. Several methods are available to curvefit this data (to determine the detectable precipitated defects) and PC software is available from RADC for this purpose.

Recalling Procedure C, screening strength is the product of precipitation efficiency and detection efficiency. Curvefitting the factory fallout data to the above expression yields the "k" value for the precipitation efficiency expression [1-exp(-kt)] and also determines DPAT and CFR. If field data is available, the Stress Adjustment Factor (SAF) and the detection efficiency of factory ESS can also be determined. The SAF can be calculated by dividing the latent defects (determined by curvefitting the field data), by the escaping latent defects (determined by curvefitting the factory data). The factory detection efficiency can be calculated by dividing the field patent defects (determined by curvefitting the

field data) by the total factory fallout. These calculations can be expressed mathematically as follows:

SAF = Dlat (field) / [Dlat (factory).(1-SS(factory))]

DE (factory) = Dpat (field)/ [Factory fallout]

Figure 5.5 illustrates a sample curvefitting analysis.

5.6 Procedure E - Monitor and Control

5.6.1 Objective. To implement a program to monitor and control the ESS program (consistent with TQM philosophy) thereby ensuring that the program remains cost effective under the evolving conditions.

5.6.2 Methodology. The parameters of interest for monitor and control are DIN, SS, and $D_{REMAINING}$ and are determined in Procedure D. Modified SPC and PARETO charts are prepared to monitor these parameters against the requirements established in Procedure A.

5.6.3 Procedure Steps.

Step 1. Management monitor and control is accomplished by preparing SPC charts for the important parameters determined in Procedure D. Since the objective of ESS is continuous improvement in the elimination of defects and their causes, a homogeneity test is not adequate for D_{IN} and $D_{REMAINING}$ since they should be decreasing with time and product maturity. The SPC charts must also reflect the requirements, (which are directly related to field reliability by $D_{REMAINING}$) the current level of performance, and the statistically expected variation due to limited sample size. With conventional SPC charts the parameter of interest remains relatively constant, so that the process average (μ) variation can be determined by taking the mean over many samples. For ESS however, the parameter of interest (μ) is expected to be improving with time making it necessary to use regression analysis. A second order polynomial regression analysis is usually adequate.

Figure 5.6 illustrates a modified SPC chart for monitoring the total incoming defects D_{IN}. It displays the TQM goals (inherently established as part of Procedure A) and compares actual results to these requirements. The expected statistical variation due to the limited sample size is calculated using a Poisson distribution and has a standard deviation given by $\delta = \sqrt{\mu/n}$ where n is the sample size and μ is determined from the regression analysis.

Step 2 As a supplement to the SPC charts created in step 1 it is sometimes useful to generate a PARETO chart to display a breakdown of failure causes. The PARETO typically examines the frequency of various causes of non-conformities and indicates defect frequency and/or frequency percentage. The PARETO identifies the most frequent cause but not necessarily the most important cause and can over look what is expected based upon other considerations, for example complexity.

To overcome this, a modified PARETO is recommended that charts not only actual results, but compares them with the expected results based on complexity and statistical significance. When reviewing the Pareto diagram, situations where

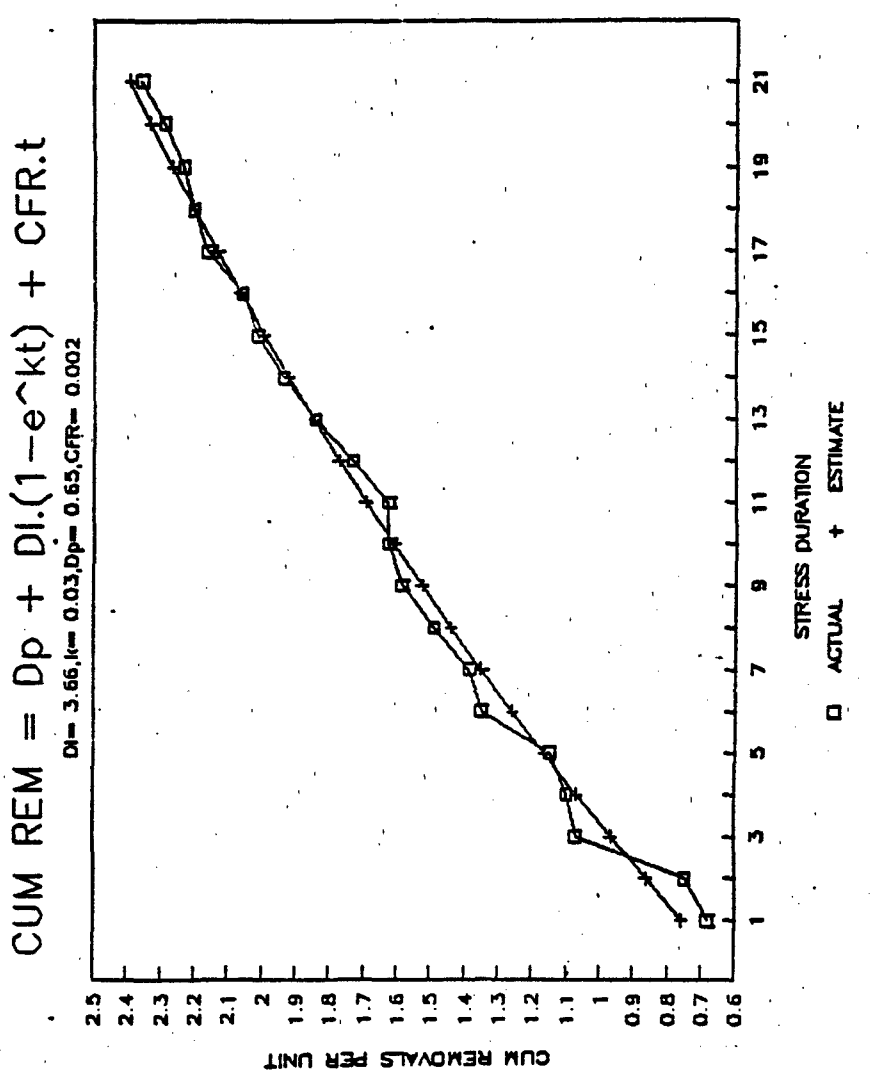


Figure 5.5 Sample Curvefitting Analysis

defects are either greater or less than expected require more in depth analysis. Since a design fault is often specific to a particular assembly, the PARETO chart can help identify potential design flaws by identifying assemblies with defect densities above expected levels. Conversely, assemblies with defect densities significantly lower than expected levels may indicate low screening stresses or low detection efficiency. If the SPC chart for a particular assembly continually trends above or below expected levels and detailed failure analyses do not reveal abnormal causes, then the cause may be to do packaging density etc. If so, the expected goals and requirements for the particular assembly can be adjusted by a suitable correction factor and Procedure A repeated. Figure 5.7 illustrates a typical application of a PARETO chart. To allow for statistical variations due to sample size, the expected values are indicated as ±3 sigma bars (assuming a Poisson distribution as for the SPC charts). This makes it possible to identify not only assemblies with high and low defect densities but also those assemblies where the defect density is significantly different than expected.

The PARETO is recommended because it not only charts actual results, but compares them with expected results based on complexity and statistical significance.

5.7 Procedure F - Product Reliability Verification Test (PRVT)

5.7.1 Objective. To retain a minimum ESS so that field reliability can be projected and out of control conditions identified.

5.7.2 Methodology. The Monitor and Control Procedures of Procedure D determine whether or not outgoing reliability requirements are being met by comparing actual factory results with the goals (established in the design stage of Procedure A) via SPC and PARETO charts. Since these procedures ensure reliability is achieved, any further testing would be redundant. Recall that the ESS program operates in a feedback loop. The intent is to precipitate defects (in the factory) that would have occurred in the field and thus identify their causes so that corrective actions can be taken to prevent their recurring. This should continually reduce defect density thereby allowing for a reduction in ESS. However, the extension of this process is to completely eliminate ESS - thereby creating a situation in which there is no mechanism to indicate when the process is not in control and reliability is not being achieved. PRVT is defined as that portion of ESS retained for the purpose of providing such a mechanism and is inherently part of the ESS program (and subject to the Monitor and Control Procedure of Procedure D).

Any assessment of reliability must be made on the basis of the performance of the collective population in the field and the percentage of systems that are defective in a specified operating period (the assessment of factory performance must be made on the same basis). It is measured by implementing a monitor and control program based on normalized parameters (defects/system, defects/unit etc). The PRVT segment is to be monitored in this way. However, first pass yield (where first pass yield is defined as the number of systems completing the PRVT segment with no failures divided by the total number of systems first time submitted) is also applicable. Provided the defects are Poisson distributed, first pass yield and defects/system requirements are related by Yield = exp (-Defects).

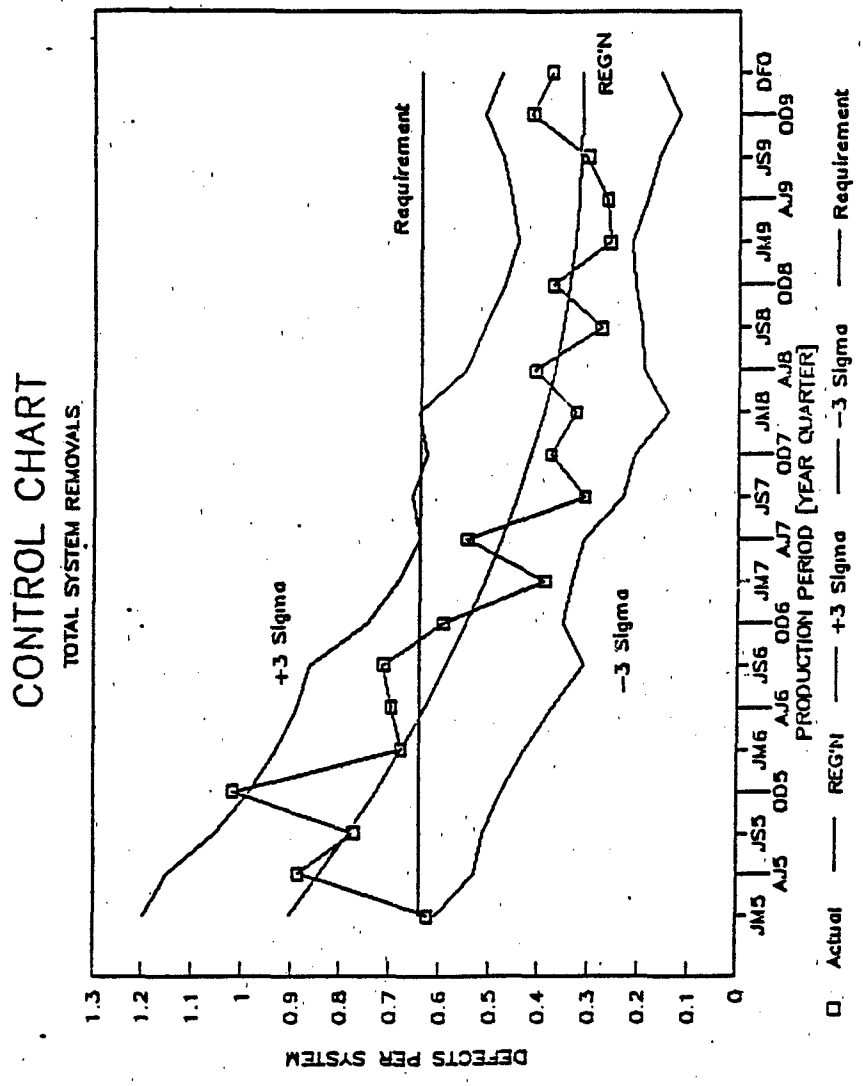


Figure 5.6 Sample SPC Chart

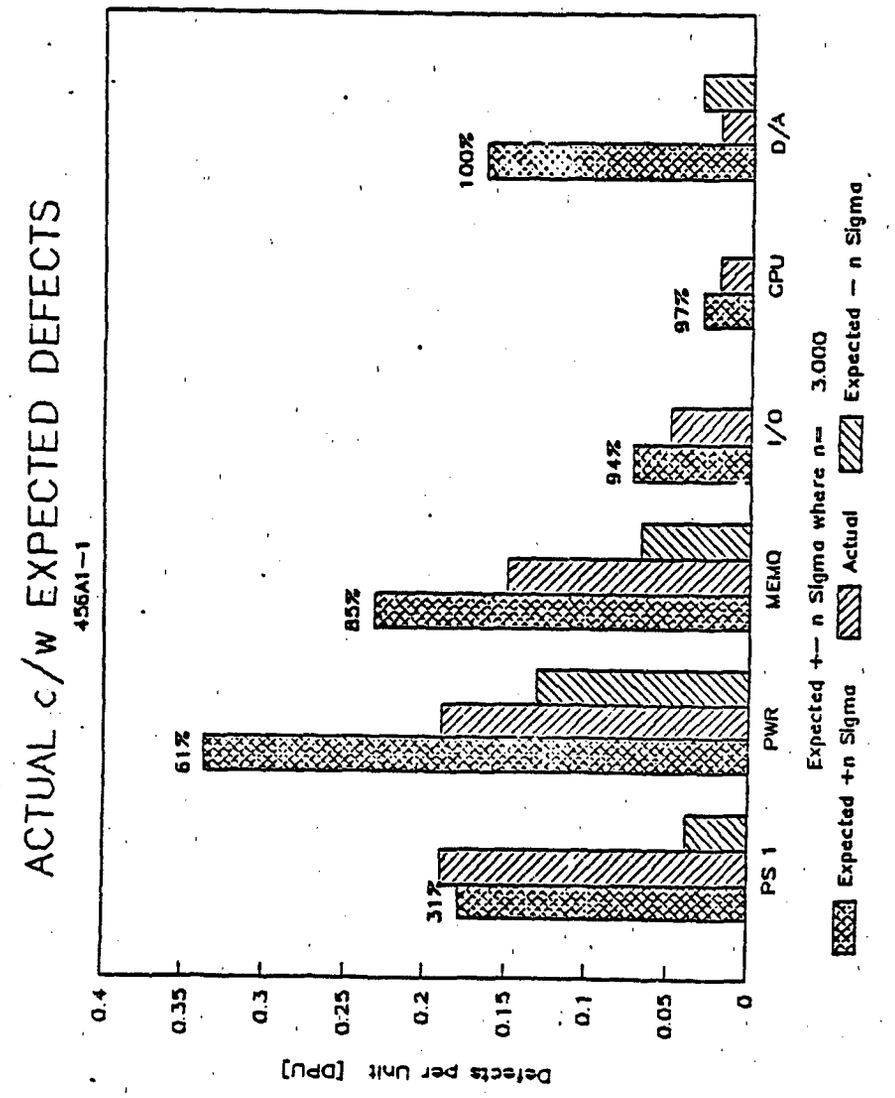


Figure 5.7 Sample PARETO Chart

If the SPC requirements (see Procedure E paragraph 5.6) and the PRVT requirements of first pass yield are not achieved, the outgoing system defect density is too high and corrective action must be taken that addresses the general population. If defect causes can not be immediately removed to attain an "in control" situation, ESS must be increased for all production (subject to the damage restrictions outlined in Procedure A) until "control" is re-established.

5.7.3 Procedure Steps.

Step 1. Using the mathematical derivations relating first pass yield to field reliability (MTBF) detailed in Appendix B, determine if the first pass yield is worse than required. If the first pass yield and the monitor and control technique of Procedure E indicates that the necessary field reliability is not being achieved, add ESS according to the methods outlined in Procedure A.

Step 2. As the ESS program evolves and ESS is reduced, ensure that as a minimum, one RV and two TC cycles are retained for the PRVT segment to help identify out of control conditions that would otherwise be missed.

APPENDIX A

Stress Screening Mathematical Model

10. General. The fundamental objective of a stress screening program is to reduce the number of latent defects in a production lot of equipment to an acceptable level by use of cost effective screening regimens. As basic principles, one would like to be able to use strong screens and efficient tests, within prescribed cost constraints, which have a high probability of precipitating and detecting defects and thus achieving reliability objectives. To transform these principles into quantitative procedures, it is necessary to define various measures and their relationships to the screening process. This Appendix defines a mathematical model that predicts/establishes relationships between quantities such as defect density, precipitation efficiency, detection efficiency, screening strength, and yield.

20. Reference documents. (See Section 2)

30. Definitions and acronyms. (See Section 3)

40. General mathematical relations.

40.1 Defect density. Under reasonable assumptions that the number of latent defects in a product are independently and identically distributed, the number of defectives in an equipment can be described by the Binomial Probability distribution, with parameters N and P.

Where N = total number of parts in the equipment
P = average part fraction defective over all part types

A part as defined herein, is any identifiable item within the product which can be removed or repaired, (e.g., discrete semiconductor, resistor, integrated circuit, solder joint, connector). For large N and small P the Binomial can be approximated by the Poisson distribution with the parameter D = NP

Where D = Defect Density (average number of latent defects per item)

The defect density D = NP can also be represented as:

$$D = N\bar{P} = \sum_{i=1}^{m} n_i p_i \qquad \text{(A-1)}$$

where: n_i = quantity of each part type i

p_i = defect density for each part type i

m = number of different part types

The procedures contained in Procedure B of Section 5, for obtaining planning estimates of defect density, are based upon the mathematical relations just described.

40.2 Precipitation Efficiency. The Precipitation Efficiency (PE) of a screen is expressed as the probability that the screen will precipitate a defect to a detectable state given that a defect susceptible to the screen is present. For ESS to be viable, the screening strength (and hence precipitation efficiency) of a screen must be independent of the number of defects and when the screen is performed. Mathematically this can be satisfied if the defects are exponentially distributed in time.

$$D_x = D_{LAT}^{(T)} [1 - \exp(-k_1 t)] \qquad (A-2)$$

where: D_x = defects precipitated

D_{LAT} = latent defect population at time T

k_1 = stress constant for precipitation

t = stress duration

Precipitation efficiencies for various screen parameters are given in Tables 5.14 through 5.17.

40.3 Detection Efficiency. In general, Detection Efficiency can be represented by a Poisson Distribution in stress duration.

$$DE(t) = DE \times DPAT [1 - \exp(-k_2 t)] \qquad (A-3)$$

where: DE = detection efficiency

D_{PAT} = existing patent defects

k_2 = stress constant for detection efficiency

t = stress duration

Provided the k terms for precipitation efficiency and detection efficiency are significantly different, the lower k term will dominate. With this simplification, detection efficiency can be considered to be independent of t and represented by the constant DE. Fixed parameters for calculating detection efficiencies are given in Procedure C in Part 5.

40.4 Screening Strength. The screening strength (SS) is defined as the product of precipitation efficiency and detection efficiency.

$$SS = PE \times DE \qquad (A-4)$$

40.5 Yield. Given prior estimates of p_i, equation A-1 can be used to estimate D_{IN}, the incoming latent defect density before assembly screening, since N and ni are known for the assemblies and equipment to be screened. The remaining defect density $D_{REMAINING}$ can be described in a similar manner, except that the pi, of equation 1, would be interpreted as the remaining part defect density. D_{IN} and $D_{REMAINING}$ are normalized quantities and can also be expressed as:

$$D_{IN} = \frac{\text{total number of latent defects introduced}}{\text{total number of equipment in the Lot}}$$

$$D_{REMAINING} = \frac{\text{total number of latent defects remaining}}{\text{total number of equipment in the Lot}}$$

Without an ESS program, a production lot of equipments will contain defects which are introduced into the equipments as escapes from previous part level screens and by poor workmanship or manufacturing processes. The defects introduced are expressed quantitatively as the average number of defects per equipment (D_{IN} or defect density). Using the Poisson probability distribution, the probability that an equipment is defective P(D) (i.e., contains one or more defects) is given by:

$$P(D) = 1 - e^{-D_{IN}} \qquad \text{(A-5)}$$

The objective of an ESS program is to reduce D_{IN} to an acceptable level, say $D_{REMAINING}$, where $D_{REMAINING}$ is defined as the average number of defects remaining per equipment at delivery to the customer. Reducing D_{IN} to $D_{REMAINING}$ also reduces P(D) so that:

$$P(D) = 1 - e^{-D_{REMAINING}} \text{ assuming all remaining defects will fail} \qquad \text{(A-6)}$$

The probability that an equipment will pass a screening test is called Yield. Because not all remaining defects fail during the screen, the expression for yield becomes:

$$\text{Yield} = e^{-D_{REMOVED}} \qquad \text{(A-7)}$$

If the Yield is specified as a goal, then $D_{REMOVED}$ can be determined by:

$$D_{REMOVED} = -\ln(\text{Yield}) \qquad \text{(A-8)}$$

and used as an objective for which an ESS program can be planned, implemented and subsequently monitored and controlled. Both $D_{REMAINING}$ and Yield are used in the handbook Procedures A and F, as the quantitative goal of the ESS program.

40.6 Remaining/Removed Defects. The quality of the ESS program and by extension, the number of defects removed is a function of five simultaneous effects:

- precipitation of latent defects;
- detection of precipitating defects (immediately and with stress time);
- detection of previously precipitated patent defects "immediately" due to different test or environment;
- detection of previously precipitated patent defects due to stress time;
- detection of "constant failure rate" defects

For mathematical purposes this can be reduced to three distinct terms:

- detection of previously precipitated latent defects;
- detection of latent defects precipitating during ESS;

- detection of defects precipitating at a constant rate i.e., determined by the limiting MTBF.

Therefore, the mathematical model can be represented by:

$$D_{REMOVED} = DE \times D_{PAT} + DE \times D_{LAT} [1 - \exp(-kt)] + DE \times CFR \times t \quad \text{(A-9)}$$

where DE = detection efficiency

D_{PAT} = patent defects

D_{LAT} = latent defects

k = stress constant

t = stress duration

CFR = constant failure rate

The remaining latent and patent defect density is given by:

$$D_{REMAINING} = (1 - DE)\, D_{PAT} + (1 - DE)\, D_{LAT} (1 - \exp(-kt)) + D_{LAT} (\exp(-kt)) \quad \text{(A-10)}$$

40.7 Chance Defective Exponential Model (CDE). The CDE model is based upon the assumption that the population of parts within a lot of like equipments is comprised of two subpopulations, i.e., a main subpopulation of "good" parts and a much smaller subpopulation of defectives. The defectives contain major flaws which degrade with stress and time and are manifested as early-life failures. The failure rate of a defective part is several orders of magnitude greater than the failure rate of a "good" part. Therefore, relatively few defectives can dominate the reliability of the equipment during early product life.

Additional assumptions, terms and definitions which are used in the CDE model are:

(a) The number of defectives in an equipment is independent and identically distributed and the distribution is Binomial with parameters N and P.

where: N = total number of parts in an equipment
P = average part fraction defective

For large N and small P the Binomial can be approximated by the Poisson distribution so that D = NP is the average number of defects per item (defect density).

$$D = N\overline{P} = \sum_{i=1}^{n} n_i p_i$$

where: n_i = quantity of part type i
p_i = fraction defective part type i

The defect density D is one of three parameters of the CDE model.

(b) The failure distribution of the "good" or main subpopulation of parts in an equipment is exponential with parameter λ_o and the reliability function is given by, $R_o(t) = e^{-\lambda_o t}$. λ_o is another parameter of the CDE model. The parameter λ_o can also be expressed as $\lambda_o = (N-D)\lambda_G$, where λ_G is the average failure rate of a "good" part

(c) The failure distribution of a defective part is exponential with parameter λ_D and the reliability function if given by $R_D = e^{-\lambda_D t}$. The parameter λ_D is defined as the average failure rate of a defective part under a particular stress environment. Note that when the CDE model is applied to a screen, $(1 - R_D) = 1 - e^{-\lambda_D t} = SS(t)$, the screening strength. Note that the average failure rate of a defective part is much greater than the average failure rate of a "good" part. i.e. $\lambda_D >> \lambda_G$ and with large defect densities the failure rate of the defective population can be greater than the population of "goods". i.e. $D\lambda_D > (N - D)\lambda_G$.

Given that a system contains n defective parts, the conditional reliability of the system $R_S(t/n)$ is:

$$R_s(t/n) = R_O(t) \cdot R_D(t)^n \qquad n = 0, 1, 2 \ldots$$

Using the Binomial the joint probability of survival and n defects present is:

$$R_S(t/n) \cdot P(n) = R_O(t) \left[R_D(t)\right]^n \left(\frac{N}{n}\right) p^n q^{N-n}$$

For large N and small P the Binomial can be approximated by the Poisson with parameter $D = NP$ so that the unconditional survival probability for any number of defects m is given by:

$$R_s(t) = R_o(t) \sum_{m=0}^{\infty} R_D(t)^m \frac{(D)^m e^{-D}}{m!} \qquad \text{(A-11)}$$

For all real values of m

Performing the summation in A-11 gives the reliability function:

$$R_S(t) = R_O(t) e^{-D\left[1-R_D(t)\right]} \qquad \text{(A-12)}$$

Using the assumptions $R_O(t) = e^{-\lambda_o t}$ and $R_D(t) = e^{-\lambda_D t}$ above; equation A-12 becomes:

$$R_S(t) = \exp\left[-\lambda_o t - D(1 - e^{-\lambda_D t})\right] \qquad \text{(A-13)}$$

The failure rate for the system $\lambda_S(t)$ is given by:

$$\lambda_S(t) = -\frac{d}{dt} \ln R_S(t)$$

resulting in: $\lambda_s(t) = \lambda_o + D\lambda_D e^{-\lambda_D t}$ (A-14)

The probability density function for the system is given by:

$$f_s(t) = \lambda_s(t) \cdot R_s(t)$$

$$\text{so that: } f_s(t) = \left[\lambda_o + D\,\bar{\lambda}_D e^{\bar{\lambda}_D t}\right] exp\left[-\lambda_o t - D(1-e)^{\bar{\lambda}_D t}\right] \quad \text{(A-15)}$$

The expected number of failures for the system is time t is given by:

$$E_S(T) = \int_O^T t \cdot f_s(t)\,dt$$

which gives: $E_s(T) = \lambda_o T + D(1-e^{-\lambda_D T})$ (A-16)

40.8 Relating DR to field reliability and failure rate. Using the CDE model the reliability and failure rate of a system which has not had ESS exposure during manufacture is given by equations (A-13) and (A-14) as:

$$R_s(t) = exp\left[-\lambda_o t - D_{IN}(1 - e^{-\bar{\lambda}_D t})\right]$$

$$\lambda_s(t) = \lambda_o + D_{IN}\lambda De^{-\lambda_D t}$$

λ_D is viewed as the failure rate of a defective under the field stress conditions to which the system will be exposed and λ_o is the limiting MTBF based on experience data.

Given the same system which has been exposed to ESS during manufacture, then D_{IN} is reduced D_R and the other model parameters λ_o and λ_D have the same interpretation as before. The failure rate function (equation A-14) both with and without an ESS program is illustrated in Fig A-1.

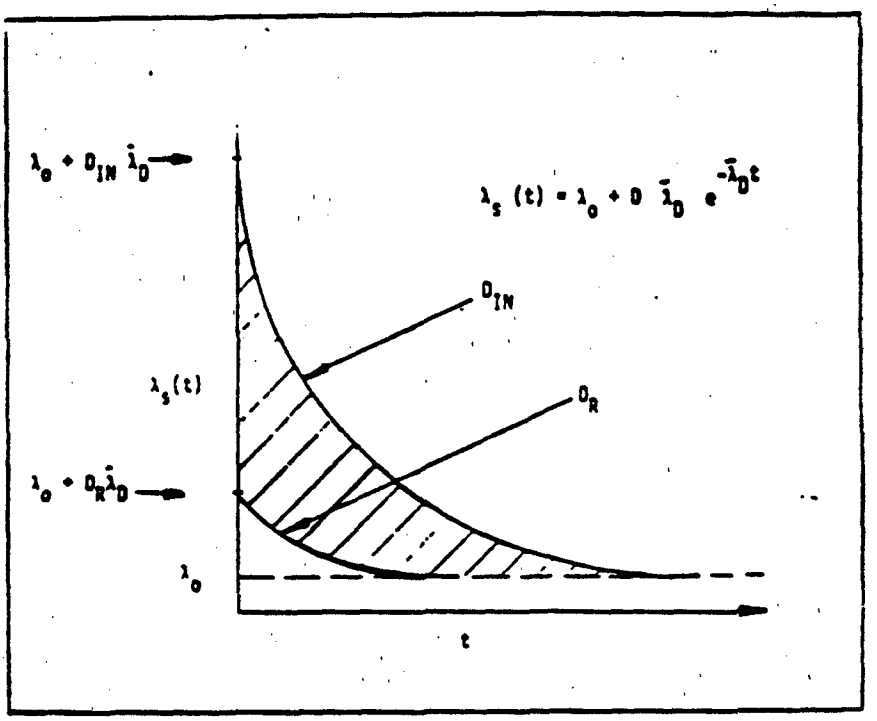


Figure A-1 Field Failure Rate vs. Defect Density

The shaded area represents the defects removed from the product as a result of the ESS program conducted during manufacture.

APPENDIX B

Product Reliability Verification Test

10. General. A product reliability verification test (PRVT) provides a means of establishing a reasonable level of confidence that the outgoing equipment is adequately free of defects and will achieve the required reliability in the intended application. The PRVT segment of the ESS program is primarily of use when the preceding ESS has been nearly eliminated through corrective actions that have reduced the incoming defect densities for parts and manufacturing. Since the PRVT is part of the ESS program the normal monitor and control procedures apply. For simplicity, it is useful to use the first pass PRVT yield as a reliability indicator.

20. Reference Documents. See section 2

30. Definitions and acronyms. See section 2

40. General Mathematical Relations.

40.1 Derivation. The objective is to establish a mathematical relationship between PRVT yield and field reliability.

From appendix A Factory yield= exp (-Dremoved) (B-1)

$$Dremoved = DE.[Dpatent + Dremaining.(1-exp(-kt)) + CFR.t] \quad (B-2)$$

The field failure rate FR is the defects removed in a time interval T divided by T;thus,FR can be expressed as follows

$$FR = ([Dpatent + Dremaining.(1-exp(-KT)) + CFR.T\ ])/T \quad (B-3)$$

since DE=1 for the field.

The failure rate for latent defects under field stress conditions is thus

$$FR = [\ Dremaining.(1-exp(-KT))]/T \quad (B-4)$$

Since the field and factory defects are related by the stress adjustment factor

$$SAF = \frac{\text{Latent Defects at field stress}}{\text{Escaping Latent Defects at factory ESS baseline stress}} \quad (B-5)$$

therefore, the field failure rate due to latent defects is related to the remaining defects at factory baseline stress according to

$$FR = [SAF.\ Dremaining.(1-exp(-kT))]/T \quad (B-6)$$

The defects removed during PRVT is given by
Din[PRVT].SS[PRVT] thus the remaining defects as a function of the defects removed is given by

Dremaining(PRVT stress)= Dremoved(PRVT).(1-SS(PRVT))/SS(PRVT) (B-7)

Substituting SS=1-exp(-kt) and Dremaining from equation B-7 gives the relationship between field failure rate and defects removed in PRVT

Dremoved(PRVT)=[exp(-kt)/(1-exp(-kt))].[FR.T /(SAF.(1-exp(-KT))] (B-8)
Using the relationship yield= exp(-Dremoved) and defining MTBF(latent)=1/FR(Latent) gives the desired relationship

Yield(PRVT)=exp-{[exp(-kt)/(1-exp(-kt))].T /[SAF.(1-exp(-KT).MTBF]}(B-9)

The values for SS or alternatively the precipitation factors for PRVT (k) and the field (K) can be determined using Procedure C.

APPENDIX C

Fault Coverage Data

Tables C.1 and C.2 provide fault coverage estimates for various automatic test systems used by electronics system manufacturers. Fault coverage estimates are defined for specific fault types, eg. digital "stuck at 1 or 0" and do not represent the complete fault spectrum. Application usage and situation sensitive faults must also be considered. Thus, the values provided in Table C.1 and C.2 are a guide and should be used with caution.

Table C.1 Fault Coverage vs Test Types

Level Assembly	Test Type	Fault Coverage
Assembly	Production Line GO-NO GO Test	0.85
	Production line In-Circuit Test	0.90
	High Performance Automatic Tester	0.95
Unit	Performance Verification Test (PVT)	0.90
	Unit Factory Checkout	0.95
	Final Acceptance Test	0.98
System	On-Line Performance Monitoring Test	0.90
	System Factory Checkout Test	0.95
	Customer Final Acceptance Test	0.99

Table C.2 Fault Coverage for Automatic Test Systems

Circuit Type	Automatic Test System Type			
	Loaded Board Shorts Tester (LBS)	In-Circuit Analyzer (ICA)	In-Circuit Tester (ICT)	Functional Board Tester (FBT)
Digital	45% to 65%	50% to 75%	85% to 94%	90% to 98%
Analog	35% to 55%	70% to 92%	90% to 96%	80% to 90%
Hybrid	40% to 60%	60% to 90%	87% to 94%	83% to 95%

As can be noted from the tables, using only a Functional Board Tester (FBT) provides 95% fault coverage but combining an In-Circuit Tester (ICT) with the FBT increased coverage to 97% and adding an In-Circuit Analyzer (ICA) to the sequence, increases coverage to 99%.

An illustration of fault coverage for a sample of 1000 PWA's subjected to various test strategies is also provided in Table C.3. The strategies employed include the use of each of four automatic testers independently and in combination.

Table C.3 Fault Detection for a 1000 PCB Lot Size

Fault Classification	Actual	LBS	ICA	ICT	FBT	ICA-ICT	ICA-FBT	ICT-FBT	ICA-ICT-FBT
Shorts	261	261	261	261	261	261	261	261	261
Opens	5	5	5	5	5	5	5	5	5
Missing Components	30		25	28	25	29	27	29	30
Wrong Components	67		53	61	55	64	59	60	65
Reversed Components	28		26	23	25	27	28	25	28
Bent Leads	43		38	43	43	43	43	43	43
Analog Specifications	25		13	21	18	21	21	22	23
Digital Logic	27			20	27	20	27	27	27
Performance	26				26		26	26	26
Total No. of Faults	512	266	421	462	486	470	497	498	508
Fault Coverage	100%	52%	82%	90%	95%	92%	97%	97%	99%
Fault Coverage Increase	-	-	-	-	-	2.2%	2.3%	2.5%	4.5%
Rejected PCBs	398	223	345	370	385	374	391	393	394
Rework Yield		195	316	354	376	361	384	388	393
Undetected Faulty PCB		203	82	44	22	37	14	10	5
Rework Yield		49%	79%	89%	94%	91%	96%	97%	99%
Rework Yield Increase	-	-	-	-	-	2%	2.1%	3.2%	4.5%
Finished Units		805	918	956	978	963	986	990	995

The faults detected are typical patent defects and do not cover the spectrum of defect types of interest in stress screening. The statistics provided in the

table, however, provide a basis for developing estimates of detection efficiency when a stress screening program is being planned. The data should also be helpful in selecting test strategies for use with stress screens.

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